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INTERSITE MAGNITUDE-YIELD BIAS EXEMPLIFIED BY THE UNDERGROUND NUCLEAR EXPLOSIONS MILROW, BOXCAR AND HANDLEY

D.H. von Seggern

Seismic Data Analysis Center

Teledyne Geotech, 314 Montgomery Street, Alexandria Virginia 22314

05 May 1978

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Estimates of surface-wave and body-wave magnitude were made from all available teleseismic WWSSN recordings of the Nevada Test Site shots BOXCAR and the Amchitka Test Site shot MILROW, in the megaton range of yield. These shots had very closely matched medium properties at the shot point. Tectonic strain release is not a significant factor in the amplitudes of either set of waves for these two shots. When averaged over common networks, and corrected for a slight yield difference, the BOXCAR m_b is approximately 0.3 less than that of MILROW while the BOXCAR M_s is approximately 0.5 larger than that of

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Another megaton shot at NTS, HANDLEY, was also analyzed to provide control. While the HANDLEY m_b is approximately equal to that of MILROW the shot point medium was substantially different and if account is made of the response of the shot point medium to a dilatant force according to the theory of Hudson and Douglas (1975), then the m_b difference between HANDLEY and BOXCAR may be accounted for theoretically. Non-linear results due to Cherry et. al. (1975) do not account for the difference between HANDLEY and BOXCAR, but the main point is that since the shot point parameters of BOXCAR and MILROW are well matched, any theory would predict equal radiated energy, whereas most theories would predict some difference between BOXCAR and HANDLEY, whose source properties are poorly matched.

The HANDLEY M_s is approximately equal to that of BOXCAR, also in accordance with the theory of Hudson and Douglas, so that M_s bias remains estimated the same as for BOXCAR-MILROW: 0.5 units

INTERSITE MAGNITUDE-YIELD BIAS EXEMPLIFIED BY THE
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ABSTRACT

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Another megaton shot at NTS, HANDLEY, was also analyzed to provide control. While the HANDLEY m_b is approximately equal to that of MILROW the shot point medium was substantially different and if account is made of the response of the shot point medium to a dilatant force according to the theory of Hudson and Douglas (1975), then the m_b difference between HANDLEY and BOXCAR may be accounted for theoretically. Non-linear results due to Cherry et. al. (1975) do not account for the difference between HANDLEY and BOXCAR, but the main point is that since the shot point parameters of BOXCAR and MILROW are well matched, any theory would predict equal radiated energy, whereas most theories would predict some difference between BOXCAR and HANDLEY, whose source properties are poorly matched.

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INTRODUCTION

The purpose of this research is to evaluate m_b and M_s bias between the Nevada Test Site (NTS) and Amchitka by means of careful absolute magnitude measurements of two matched events, BOXCAR and MILROW.

Since the inception of underground testing of nuclear explosives, seismic measurements have performed a central role in estimating yields. More recently, this role has assumed added importance because of problems inherent in verification of proposed test ban treaties based on a threshold, or upper limit, to the allowable yield of the underground explosions. In this case, the precision of mapping between observed seismic magnitudes and energy yields (commonly expressed as kilotons of equivalent chemical explosive) is required to be better than that normally expected in the seismological community for the energy release of earthquakes.

In estimating yields from events at a new test site from seismic data, a "true" magnitude is sought that maps one-to-one into yield. This true magnitude must first be biased by the physical properties of the detonation media, the geological setting of the test site, and the constitution of the crust and upper mantle below the source. These aspects are "source effects", and their cumulative effect is termed "source bias". The source bias may in principle be removed by theoretical analysis using geophysical data. Addition of source bias to the true magnitude produces "operational magnitude", which a teleseismic network well-distributed in distance and azimuth would report if all stations recorded. However, since the scatter of individual magnitudes about the mean event magnitude is known to have a standard deviation of roughly 0.3, (Evernden and Kohler, 1976), the true magnitude is subject to further distortion when recorded by a small or poorly-distributed network. Station corrections may minimize the problem if they can be determined. However, to determine corrections a good absolute magnitude must be obtained for a calibration shot (the object of this report) and then a relation between absolute magnitude and yield must be available. Another possibility of course is to have a known

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Evernden, J. F., and W. M. Kohler, 1976. Bias in estimates of m_b at small magnitudes, Bull. Seism. Soc. Am., 66, 1887-1904.

yield for one event and to determine yields of other nearby events relative to that event.

Use of common stations in comparing magnitudes will remove some relative scatter. However, azimuthally-dependent amplitude anomalies have been found (e.g., NORSAR subarrays, in Husebye, Dahle, and Berteussen, 1974). Although published yields exist for numerous underground explosions at the Nevada Test Site (Springer and Kinnaman, 1971), data for other test sites is scant. Evernden (1970), using LRSM data from North American sites, published m_b-yield data for various detonation media at NTS and for the LONGSHOT detonation at Amchitka. There was considerable scatter among the NTS points, which included low m_b's for alluvium and high m_b's for Pahute Mesa tuffs, but only slightly higher m_b for LONGSHOT than for Pahute Mesa tests. Basham and Horner (1973), using Canadian network magnitudes, added a third test site in the Sahara, which had a high m_b as compared to yield according to their data. Again, scatter was considerable, up to one unit of magnitude at a given yield. Since in both these studies of m_b-yield, m_b values were obtained from networks with limited azimuthal and distance ranges, with many stations in the regional range for NTS, the possibility of bias in the m_b between test sites is strong. On the other hand, Marshall et al. (1971) published M_s versus assumed or known yields for eight distinct sites. The data had small scatter, suggesting that M_s may be a better estimator of yield than m_b. Note that recording networks in that study were not identical and that the apparently small variation in source bias may be a fortuitous result of offsetting source and receiver biases. Yet,

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Husebye, E. S., A. Dahle, and K. A. Berteussen, 1974. Bias analysis of NORSAR and ISC reported seismic event m_b magnitudes, J. Geophys, Res., 79, 2967-2978.

Springer, D. L., and R. L. Kinnaman, 1971. Seismic source summary for U. S. underground nuclear explosions, 1961-1970; Bull. Seismol. Soc. Am., 61, 1073-1098.

Evernden, J. F., 1970. Magnitude versus yield of explosions, J. Geophys Res., 75, 1028-1032.

Basham, P. W., and R. B. Horner, 1973. Seismic magnitudes of underground nuclear explosions, Bull. Seism. Soc. Am., 63, 105-132.

Marshall, P. D., A. Douglas, and J. A. Hudson, 1971. Surface waves from underground explosions, Nature, 234, 8-9.

the apparent superiority of M_s over m_b in estimating yield was suggested theoretically by Hudson and Douglas (1975) and by Bouchon (1976) who showed the near insensitivity of M_s to changes in the elastic parameters at the detonation depth compared to the high sensitivity of m_b (based on short-period recordings) to these same changes.

Analysis of previous work on magnitude-yield indicates that, because of possible network bias, no completely satisfactory estimates of magnitude-yield relations for distinct test sites have been achieved. Moreover, no separation and quantification of source and receiver bias has been accomplished. Paucity of yield data at sites other than NTS prevents finding significant results at this time for all the known nuclear explosion sites, thus limiting the scope of this report. By taking two sites with published yield estimates for high-energy, well-recorded detonations, a large, common, global recording network can be used to minimize receiver bias and pinpoint any existing source bias. The sites selected are Amchitka Island and Pahute Mesa at NTS. Liebermann and Pomeroy (1969) and Ward and Toksöz (1971) have already suggested significant difference between the two sites in terms of m_b versus yield or M_s versus yield or both. Specifically, the two explosions MILROW and BOXCAR are studied because they are nearly of equivalent yield (1000 and 1200 kt, respectively, according to the listing of Springer and Kinnaman (1971) and because, as we shall see, the shot media of BOXCAR is a good match for that of MILROW. Another event, HANDLEY, whose shot medium is a poor match to MILROW is also studied. Results presented here clearly reveal a difference in both m_b and M_s for megaton shots at these two test sites. Attempts are made to identify the causes of this source bias through analysis of selected signals and study of the source environment.

Hudson, J. A., and A. Douglas, 1975. On the amplitudes of seismic waves, Geophys. J., 42, 1039-1044.

Bouchon, M., 1976. Teleseismic body-wave radiation from a seismic source in a layered medium, Geophys. J., 47, 515-530.

Liebermann, R. C., and P. W. Pomeroy, 1969. Relative excitation of surface waves by earthquakes and underground explosions, J. Geophys. Res., 74, 1575-1590.

Ward, R. W., and M. N. Toksöz, 1971. Causes of regional variation of magnitudes, Bull. Seism. Soc. Am., 61, 649-670.

GEOLOGICAL SETTING

The two sites chosen for this study are geologically distinct. Underlying the Amchitka test site, in the middle of the Aleutian Arc, is a complex dipping-plate structure within a basically oceanic environment; the Nevada test site is within a comparatively uniform continental structure, within the Basin-Range Province. The brief descriptions of the two environments below are an essential part of the framework for understanding and interpreting later results.

Amchitka Test Site

Amchitka Island is composed of volcanic flows and tuffaceous deposits of Tertiary age and consolidated sedimentary derivatives. The main feature of a cross-section of the crust and upper mantle structure surrounding the Amchitka test site in a N-S profile is a dipping lithospheric plate (Engdahl, 1972). The gross structure and physical properties are difficult to describe and it is certainly not helpful to characterize the region with a plane-layered earth model. Amchitka Island is bounded by the Aleutian trench on the south and by the structurally distinct Bowers Ridge on the north. South of the Aleutian trench exists oceanic structure with approximately an 11-km crustal thickness, while to the north of Bowers Ridge exists ocean-like structure under the Bering Sea with approximately a 14-km crustal thickness (Murdock, 1969). Bowers Ridge is of limited east-west extent and appears to have crustal depths to roughly 20 km or more and structure similar to the main Aleutian Arc, for which Jacob and Hamada (1972) established a velocity-depth profile from Rayleigh-wave phase velocities. They state that their data is consonant with Helmberger's (1968) interpretation of no distinct crust-mantle transition under the Aleutian Islands. "Crustal depth" under Amchitka itself could be as much as 40 km (Engdahl, 1972; Hasegawa, 1972), although this is poorly determined.

Engdahl, E. R., 1972. Seismic effects of the MILROW and CANNIKIN nuclear explosions, Bull. Seism. Soc. Am., 62, 1411-1423.

Murdock, J. N., 1969. Crust-mantle system in the central Aleutian region - a hypothesis, Bull. Seism. Soc. Am., 59, 1543-1558.

Jacob, K. H., and K. Hamada, 1972. The upper mantle beneath the Aleutian Island Arc from pure-path Rayleigh-wave dispersion data, Bull. Seism Soc. Am., 62, 1439-1455.

Helmberger, D. V., 1968. The crust-mantle transition in the Bering Sea, Bull. Seism. Soc. Am., 58, 179-214.

The boundaries of the dipping lithospheric plate have been defined by seismicity (Engdahl, 1972), by teleseismic travel-time analysis (Jacob, 1972), and by teleseismic amplitude analysis (Julian and Davies, 1972). The most important effect on m_b determined in this report, stemming from the anomalous structure under Amchitka, is the focusing and defocusing effect of the down-going slab on teleseismic raypaths, as illustrated by Julian and Davies, (1972). Although a high-attenuation zone may exist in the upper mantle above the down-going plate (Jacob, 1972), similar to that found for numerous other arcs, the position of MILROW relative to the plate is such that no teleseismic ray would pass through this zone, see Barazangi et. al. (1975).

The possibility of tectonic strain release and concomitant tsunamis from nuclear detonations on Amchitka Island has received considerable attention. The energy flux in the immediate area of Amchitka Island was two to three orders of magnitude higher than that around the Nevada Test Site (Lomnitz, 1974). This situation coupled with past observations of strong tectonic strain release from typically high-yield NTS explosions, was the basis of concern. However, the natural seismicity in the Amchitka Island region is almost wholly associated deep tectonic stresses acting upon the dipping lithospheric plate at a depth of 30 or more km below the test site, and there is no natural activity on the island itself (Engdahl, 1972). Amchitka, then, is basically decoupled from the vigorous tectonic process occurring below it. Several other arguments

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Hasegawa, H. S., 1972. Analysis of amplitude spectra of P-waves from earthquakes and underground explosions, J. Geophys, Res., 77, 3081-3096.

Jacob, K. H., 1972. Global tectonic implications of anomalous seismic P travel-time from the nuclear explosion Long Shot, J. Geophys, Res., 77, 2556-2573.

Davies, D., and B. R. Julian, 1972. A study of short-period P-wave signals from Long Shot, J. Geophys., 29, 185-202.

Barazangi, M., W. Pennington, and B. Isacks, 1975. Global study of seismic wave attenuation in the upper mantle behind island arcs using pP waves, J. Geophys. Res., 80, 1079-1092.

Lomnitz, C., 1974. Global Tectonics and Earthquake Risk, Elsevier Scientific Publ. Co., New York, NY.

for low tectonic stress at the Amchitka test sites, as stated by Engdahl, are: (1) marine terraces indicate relative stability in recent geologic time, (2) fault displacements produced by Amchitka shots are less than those produced by typical NTS shots of similar yield, and (3) ambient stress levels measured in situ on the island are low. Any tectonic strain release is pertinent to this study, in terms of its affect on m_b and M_s estimates of MILROW presented here, and an attempt will be made to estimate this contribution.

Nevada Test Site

The Nevada Test Site is an area of tuffaceous volcanic deposits and granite and rhyolite intrusives amid Paleozoic and Pre-cambrian sedimentary outcrops. It includes considerable alluvium fill in the valleys, not a typical geology for the Basin and Range Province in which it is located. The crustal and upper mantle structure, is not considered to be as complex as Amchitka, and is often modeled by a plane-layered structure. This structure is well known to be anomalous compared to normal continental regions, as indicated by shallow crustal depths (Prodehl, 1970), low upper mantle velocities (Archambeau et al., 1969; Helmberger, 1973; Biswas and Knopoff, 1974) and accompanying low Q (Solomon, 1972; Helmberger, 1973; Der and McElfresh, 1976). In this report, the low Q is relevant to mb determinations for BOXCAR. Der and McElfresh (1976)

Prodehl, C., 1970. Seismic refraction study of crustal structure in the western United States, Bull. Geol. Soc. Am., 81, 2629-2646.

Archambeau, C. B., E. A. Flinn, and D. G. Lambert, 1969. Fine structure of the upper mantle, J. Geophys, Res., 74, 5825-5865.

Helmberger, D. V., 1973. On the structure of the low-velocity zone, Geophys. J., 34, 251-263.

Biswas, N. N., and L. Knopoff, 1974. The structure of the upper mantle under the United States from the dispersion of Rayleigh-waves, Geophys, J., 36, 515,539.

Solomon, S. C., 1972. Seismic wave attenuation and partial melting in the upper mantle of North America, J. Geophys, Res., 77, 1483-1402.

Der, Z. A., and T. W. McElfresh, 1976. The effect of attenuation on the spectra of P-waves from nuclear explosions in North America, SDAC-TR-76-7, Teledyne Geotech.

linked the low Q to an attenuation of P-wave amplitudes on short-period recordings at NTS by a factor of roughly two compared to those recorded at stations located on a shield.

The natural seismicity around the Nevada Test Site is confined to the upper crust. It is often associated with visible high-angle faults and it is basically of normal type related to the continuing extensional strain of the Basin and Range Province (Scholz et al. 1971). Tectonic strain release is well documented for explosions at the Nevada Test Site (Toksöz and Kehrer, (1972A), and it is a factor that must be considered in the study of BOXCAR magnitudes. In addition to observations from explosions themselves, the number and magnitude of explosion-induced earthquakes after large detonations, such as BENHAM, provides further evidence of appreciable strain release at NTS (Hamilton and Healy, 1969). The level of induced seismicity that Engdahl (1972) observed for Amchitka explosions is roughly two orders of magnitude less than that for similar-yield tests at NTS.

Scholz, C. H., M. Baranzangi, and M. L. Sbar, 1971. Late Cenozoic evolution of the Great Basin, western United States, an ensialic interarc basin; Bull. Geol. Soc. Am., 82, 2979-2990.

Toksöz, M. N., and H. H. Kehrer, 1972a. Tectonic strain release by underground nuclear explosions and its effect on seismic discrimination; Geophys. J., 141-161.

Hamilton, R. M., and J. H. Healy, 1969. Aftershocks of the BENHAM nuclear explosion, Bull. Seism. Soc. Am., 59, 2271-2282.

STRUCTURE PROXIMATE TO THE DETONATIONS

Although gross regional structures around ATS and NTS differ considerably, Orphal et al. (19) presented physical property measurements indicating that the media proximate to the MILROW and BOXCAR detonations are similar. Table I summarizes data pertaining to the detonation points of BOXCAR and MILROW and for a comparison event HANDLEY taken from several sources.

The majority of the data are taken from the Lawrence Livermore data bank, courtesy of P. Moulthorpe. However, data for MILROW was obtained from well logs supplied by F. App, and the shear strength values were obtained from R. W. Terhune, who determined them by use of a finite element model determined relation between shear strength and cavity radius. Cavity radii were measured for the events BOXCAR and HANDLEY, but not for MILROW. Thus, to obtain a shear strength for MILROW, Terhune suggested that we assume the value obtained using a cavity radius measurement of CANNIKIN. For details on the technique used by Terhune to determine these shear strengths see Terhune and Glenn (1977).

The first point which is clear upon inspection of the material properties in Table I is that the events MILROW and BOXCAR are very similar to each other whereas the HANDLEY medium is significantly slower and weaker. All shots are well below the water table so that there is no dry porosity which Cherry et al., (1975) and others have found both experimentally and theoretically to result in a large decrease in magnitude.

Hudson and Douglas (1975) have pointed out the classical elastic result that a point dilatation force (such as a pressure time history on the interior surface of a small spherical void) results in a radiated displacement in an infinite medium proportional to $(\rho\alpha^3)^{-1}$, where ρ is the density and α is the compressional velocity. With the parameters in Table I this would result in MILROW having a magnitude 0.08 m_b less than BOXCAR, and HANDLEY having a magnitude 0.43

Orphal, D. L., C. T. Spiker, L. R. West, and M. D. Wronski, 1970, Analysis of seismic data - MILROW event, Report NVO-1163-209, Environmental Research Corp., Falls Church, VA.

Terhune, R. W., and H. D. Glenn, 1977. Estimate of earth media shear strength at the Nevada Test Site, UCRL-52358, Lawrence Livermore Laboratory, University of California, Livermore, California.

Cherry, J. T., N. Rimer, and W. O. Wray, 1975. Seismic coupling from a nuclear explosion: the dependence of the reduced displacement potential on the nonlinear behavior of the near source rock environment, SSS-R-76-2742, System, Science, and Software, La Jolla, California.

TABLE I

Physical Properties of the Medium for MILROW, BOXCAR, HANDLEY

	MILROW	BOXCAR	HANDLEY
Hole	A2	T 20i	T 20m
Depth (m)	1217	1165	1207
Medium	Basalt	Rhyolite	Tuff
ρ (shot point)	2.1 (1)	2.12	2.20
α (km/sec)	4.75 (1)	4.45	3.16
Water (wt %)	5 (2)	9	12
Dry Porosity	Saturated	Saturated	Saturated
Shear Strength, Y (bars)	190 (3)	240 (3)	95 (3)
ρ (w.p. to surface)	2.13	1.93	2.13
Overburden (bars)	254	220	252
Δm_b Hudson and Douglas (1975) relative to BOXCAR (elastic) due to α and ρ	-0.05	0.0	+0.28
Δm_b Cherry et. al. (1976)			
α	+0.05	0.0	- -0.3 ?
water	+0.08	0.0	-0.05
α + water	+0.13	0.0	-0.35

(1) log of UAE-2, (F. App), personal communication)

(2) From 9.85% porosity in well-log supplied by F-App. This is the low value for the whole column, values of 25% porosity and 11% porosity are indicated to lie within 100 meters of shot depth, suggesting true water weight % higher than 5%, up to 12%, and thus closer to the 9% BOXCAR value.

(3) R. W. Terhune (personal communications) using observed cavity radii. The scaled CANNIKIN radius was used for MILROW since the log for UAE1 shows no significant difference between CANNIKIN and MILROW shot depths.

m_b larger than BOXCAR. This would be the size effect in a homogeneous medium. However, Hudson and Douglas also point out that if the wave must go through an interface to another material then there is an amplitude factor transmission of $(2\rho\alpha)/(\rho\alpha+\rho'\alpha')$ where the prime signifies the lower material; and furthermore there is another geometrical spreading factor of $(\alpha'/\alpha')^{1/2}$. For the case of a common sub-layer with $\rho = 2.5$ and $\alpha = 5.0$; the net effect of all these factors results in MILROW having a magnitude $0.05m_b$ less than BOXCAR, and HANDLEY having a magnitude 0.28 larger than BOXCAR. As we shall see, the BOXCAR/HANDLEY difference is in good accord with observation; the small difference between MILROW and BOXCAR suggests that any major difference between their teleseismic magnitudes must be traced to a cause not at the source.

One may easily question whether the model of a dilatational force of constant amplitude is appropriate for a constant yield explosion in different media. Cherry et. al, (1976) have presented a more fundamental approach to the problem in that they use non-linear calculations as a function of elastic parameters and then compute the variation in the radiation of that RDP as these same elastic parameters vary. The elastic formulas derived by Cherry et. al. do not agree with those of Hudson and Douglas. Cherry et. al. find the radiated displacement in a two-layer medium to be proportional to $\alpha^{1.0}$ times the RDP whereas the Hudson and Douglas product $[(2\rho\alpha)/(\rho\alpha + \rho'\alpha')]^{1/2}$ is proportional to some function between $\alpha^{1/2}$ and α^{1}. One contribution to this small discrepancy is that Cherry et. al. give (α/α') as the effect of geometrical spreading instead of the $(\alpha/\alpha')^{1/2}$ given by Hudson and Douglas.

In any event Cherry et. al. carried out calculations of the effect on m_b of varying α while other parameters were held constant. Their discussion of their Figure 3.3 asserts that a 6% change in α yields a $0.05m_b$ change. This result implies that MILROW would have a magnitude $0.05m_b$ greater than BOXCAR, and HANDLEY would have a magnitude $0.3m_b$ less than BOXCAR.

Cherry et. al. also show that an increasing water weight percent decreases the coupling. The differing percents in Table I yield a MILROW magnitude 0.08 m_b larger than BOXCAR. Note from the notes in Table I that the water percent for MILROW may be low, such that the Δm_b between MILROW and BOXCAR using the tabulated water fractions would be over-estimated.

COMPARISON OF P-WAVE MAGNITUDE

Several previous estimates of the m_b of MILROW and BOXCAR are listed in Table II. The average difference is roughly 0.3 higher m_b for MILROW, an estimate affirmed in this study. New estimates for m_b's of MILROW and BOXCAR in this report were based upon all available short-period vertical recordings from stations in the WWSSN. These recordings were examined for P waves, measurements of amplitude and period were made, and magnitude was computed with as log (A/T) (Vanek et. al., 1962) using Veith and Clawson (1972) distance correction terms. Although many WWSSN recordings for these two explosions had too high an amplitude to be clearly recorded, use of two lower-yield explosions in this study would entail unacceptably few recordings of LR waves, a fact made clear by the few number of visible LR waves at WWSSN sites for MILROW. The requirement for a network totally common to the two explosions left only the twenty-three WWSSN Stations listed in Table III. However, as Figures 1a and 1b show, distribution of the network in azimuth and distance is excellent in both cases. Note that no regional stations are included in this comparison. With this network the mean operational m_b's for the two explosions are statistically established to within $\doteq$ 0.15 magnitude unit at 95% confidence. The difference in the means is established to be 0.26 ± 0.18 at 95% confidence.

Effect on the m_b measurement of the pP phase may be significant because changes of delay times produce fluctuations of not only the period but the recorded amplitude as well. For typical depths of burial theoretically a more precise measure of magnitude difference should result from measurement of the peak amplitude of the compressional break. Of course the pP time for BOXCAR and MILROW should be nearly identical since depth and velocity are closely matched. These relative m_b's should be unaffected in this case.

Vanek, J., A. Zatopek, V. Karnick, N. V. Kondorskaya, Yu. V. Riznichenko. E. F. Saverensky, S. L. Solv'ev, and N. V. Shebalin, 1962. Standardization of magnitude scales, Izv. Geophysics Series, No. 2 (1962), 153-158 English

Veith, K. F., and G. E. Clawson, 1972. Magnitude from short-period P-wave data, Bull. Seism. Soc. Am., 62, 435-452.

TABLE II

Previously published estimates of M_s and m_b for the MILROW and BOXCAR underground nuclear explosions

MILROW

M_s	m_b	ΔM_s	Δm_b	Source
5.0	6.5		0.2	NEIS
	6.4		0.2	ISC
5.17		-0.05		Marshall et al. (1971)
5.21	6.53	-0.11	0.32	Basham & Horner (1973)
5.3	6.7	-0.2	0.5	Evernden & Filson (1971)
4.99	6.44	-0.59	0.26	This paper

BOXCAR

M_s	m_b	Source
	6.3	NEIS
	6.2	ISC
5.33		Wagner (1970)
5.22		Marshall et al. (1971)
5.1	6.2	Evernden & Filson (1971)
5.32	6.21	Basham & Horner (1973)
5.1	6.0	Ward & Toksöz (1971)
5.58	6.18	This paper

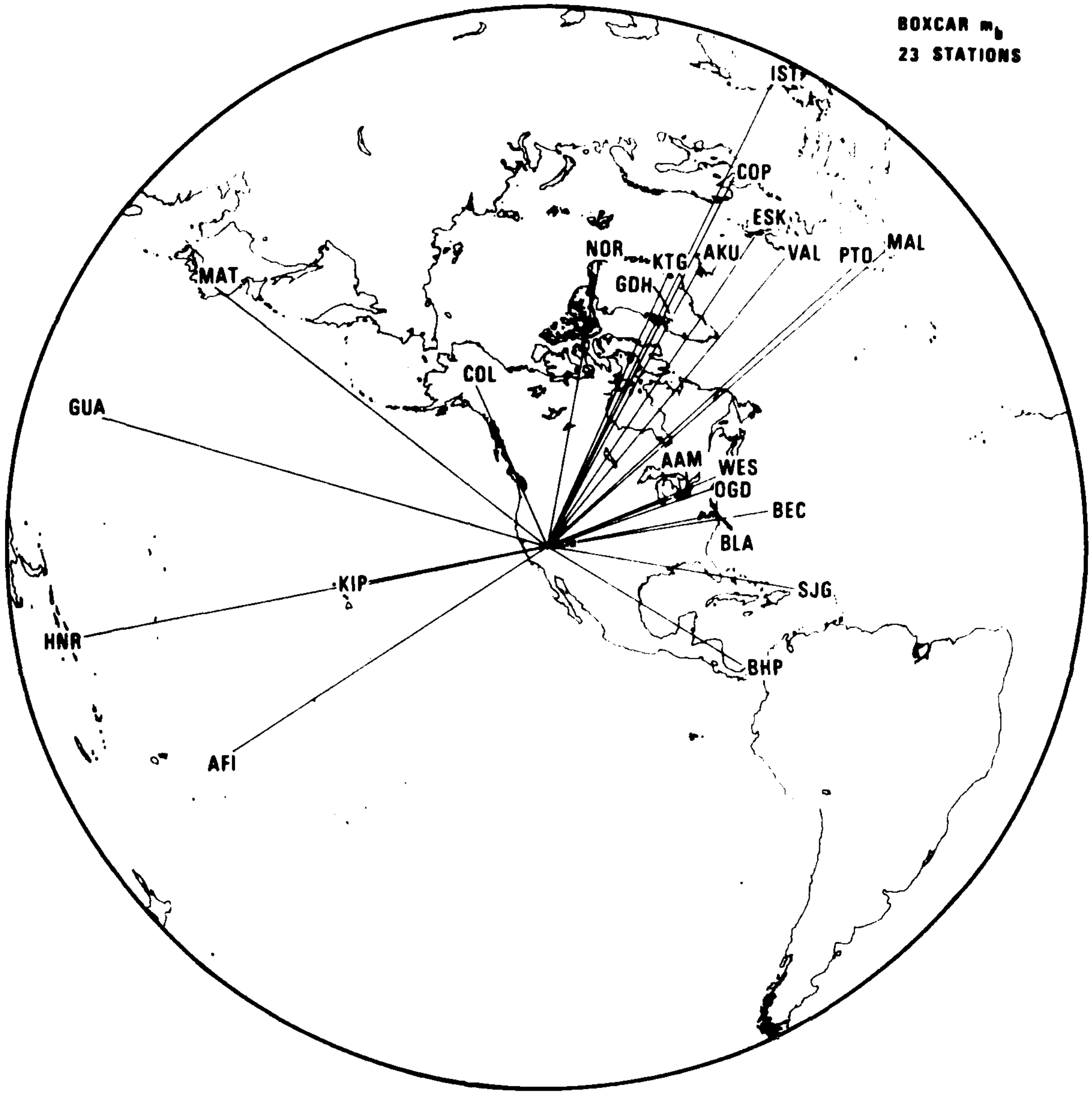

Figure 1a Locations of WWSSN stations used to estimate BOXCAR m_b (equidistant azimuthal projection from the Nevada Test Site).

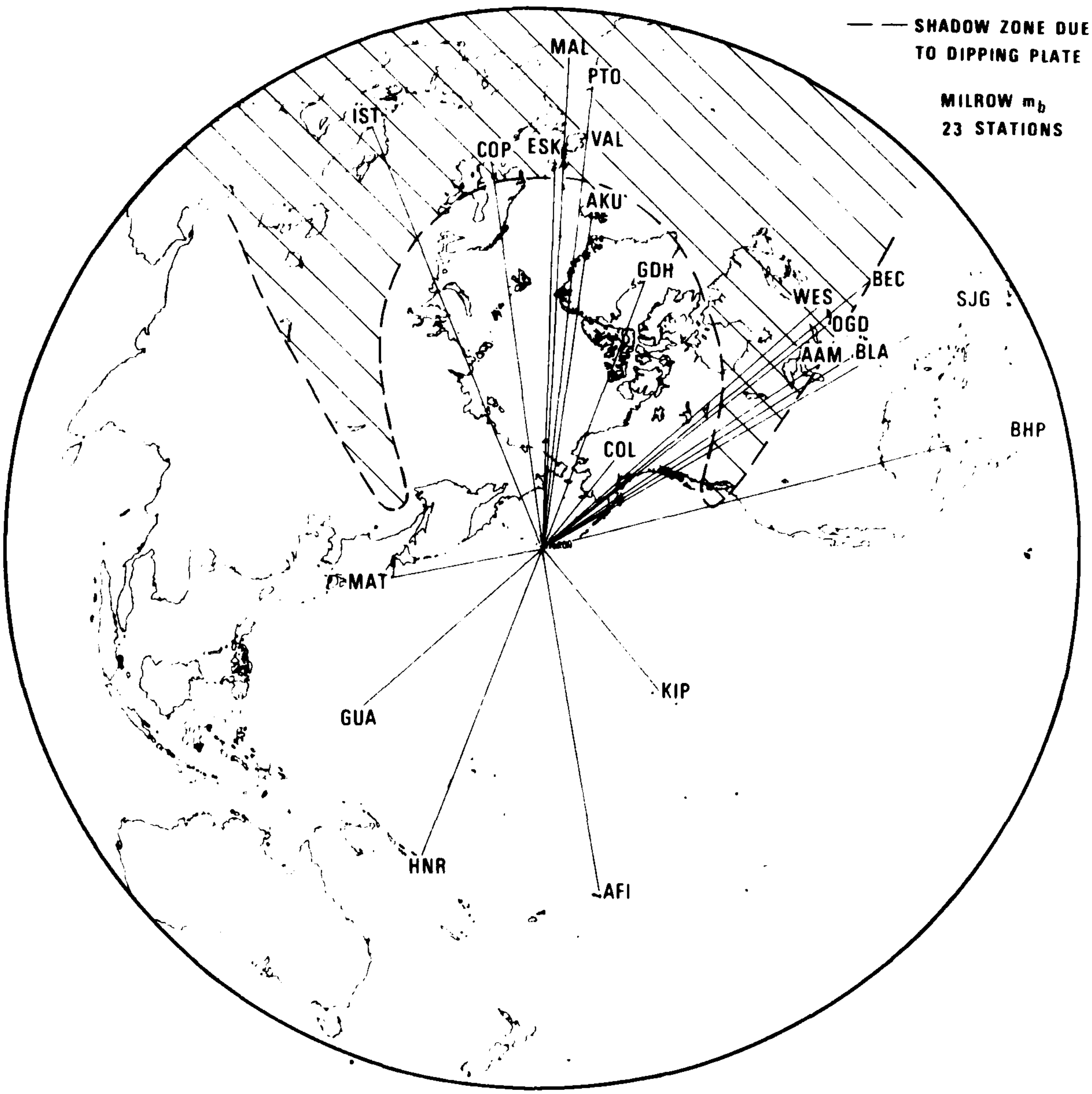

Figure 1b Locations of WWSSN stations used to estimate MILROW m_b (equidistant azimuthal projection from Amchitka Island).

The m_b values obtained in this way are also listed in Table III, and the MILROW-BOXCAR difference is reduced by 0.05 over the routine m_b difference. In another approach, m_b was computed not using the periods actually measured at each station, but a period of 1.0 uniformly; the average results were nearly identical to the standard magnitudes of Table III. This is an important point because of the uncertainty in many period measurements which might cause disagreement amoung analysts.

TABLE III

WWSSN m_b estimates for MILROW and BOXCAR

Station	BOXCAR m_b	BOXCAR $m_b(a)$*	MILROW m_b	MILROW $m_b(a)$*
AAM		5.79		5.91
AFI	6.51	5.41	6.02	5.54
AKU	5.88	5.21	6.54	5.53
BEC	6.30	5.39	6.59	5.75
BHP	5.81	4.66	6.99	6.06
BLA		6.05		5.76
COL		5.42		4.82
COP	5.84	5.14	6.46	5.77
ESK	6.23	5.45	6.46	5.67
GDH	6.15	5.24	6.31	5.64
GUA	6.47		6.37	
HNR	6.87	6.00	6.57	5.35
IST	5.61		5.78	
KIP	6.33	5.23	6.90	6.14
KTG	6.18	5.49	6.58	5.46
MAL	6.19	5.36	6.13	5.42
MAT		6.02		5.88
NOR	5.57	4.80	5.94	5.31
OGD	6.64	5.47	6.45	5.52
PTO	6.02	5.28	6.28	5.68
SJG	6.64	5.66	6.73	5.67
VAL	6.06		6.72	
WES	6.11		6.59	
Mean	6.18	5.42	6.44	5.63
Standard deviation	.35	.37	.31	.30

*$m_b(a)$ - m_b computed using the first compressional half-cycle amplitude

CAUSES OF BODY WAVE MAGNITUDE DIFFERENCE BETWEEN BOXCAR, MILROW, AND HANDLEY

The estimate of the m_b difference for MILROW-BOXCAR, made from a common global network, is 0.26. If a correction for the yield ratio is made (1200/1000) for BOXCAR/MILROW), this difference is 0.34. The possible causes of the observation are: coupling efficiency, the effect of secondary phases on the recorded amplitudes, the influence of laterally varying structure beneath the two sources, and different attenuation factors.

Coupling

Previously, the coupling difference between MILROW and BOXCAR has been inferred to be small. Although an accurate estimate could best be obtained by dynamic modeling, additional data for the model parameters would need to be gathered. Perret and Bass (1974) reported that peak and residual vertical displacement near ground-zero for BOXCAR was <u>less</u> than for MILROW and the rise times were roughly the same, but this author thinks that the BOXCAR data is insufficient to make meaningful comparison. Thus, no firm conclusions can be made concerning relative coupling efficiencies.

Secondary Phases

At the stated depths and yields for BOXCAR and MILROW, the effect of pP on the measured amplitude relative to that for P alone using WWSSN recordings will amount to between +.1 to +.2 m_b unit. These conclusions are reached by computation of theoretical seismograms using a suitable megaton source function. Thus, if BOXCAR had no appreciable pP reflection while MILROW did, part of BOXCAR'S .3 m_b decrease relative to MILROW could be accounted for.

The complex cepstral technique has been applied to these two explosions in order to identify the secondary-phase amplitudes and delay times. For MILROW, LRSM stations KN-UT, RKON, LC-NM, and HN-ME were processed; this was the same group that Bakun and Johnson (1973) used. In addition, the MILROW recording at EKA was processed. These stations were all teleseismic and showed good S/N ratios to at least 2.5 hz, the cutoff frequency used here. The data were sampled at 20/sec and bandpass filtered to eliminate energy

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Bakun, W. H., and L. R. Johnson, 1973. The deconvolution of teleseismic P-waves from explosions MILROW and CANNIKIN, <u>Geophys. J.</u>, <u>34</u>, 321-342.

above this frequency before decimating to 5 samples/sec. Individual stations' complex cepstra were windowed with a division at 0.8 sec (the pP arrival time according to uphole records), to recover the source function and the echo train, and individual results were stacked after normalizing by the rms of the respective outputs. The resulting source function and impulse train, shown in Figure 2, are nearly identical to Bakun and Johnson's (1973). A set of five stations was also processed in the same manner for BOXCAR. The stations, selected as teleseismic and having good S/N ratio to 2.5 hz, were the LRSM sites NP-NT, HN-ME, and SV-QB and the arrays EKA and YKA. For BOXCAR, the long-time and short-time windows were split at the pP uphole time of 1.0 sec. Resulting stacked output is also displayed in Figure 2. Bakun and Johnson interpret as spallation signal the broad positive motion for MILROW between one and three seconds after origin time in the echo train. The sharp negative pulse corresponding to MILROW pP arrives at the proper time of 0.8 seconds, and its reduced amplitude relative to P is indicative of the transfer of energy into the spallation phenomenon. For BOXCAR, the echo train shows a sudden upward swing at roughly 0.2 seconds, reflected at that time in the distorted appearance of the source pulse. This pulse, thought to be source related, was apparent on most processed results for the five individual stations. Shumway and Blandford (1977) identified such a phenomenon for several other explosions at Pahute Mesa in NTS using a maximum-likelihood method of processing to detect secondary signals. The cause could be multipathing through the complex structure underlying Pahute Mesa (Spence, 1974). The presence of such a multipath signal within the 1.0 short-time window used for recovering the source impulse degrades estimation of the primary signal. Figure 2 shows that the width of the BOXCAR source impulse is greater than MILROWS's. This can be attributed either to higher attenuation under the NTS than under Amchitka or to a real difference in

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Shumway, R., and R. R. Blandford, 1977. On detecting and estimating multiple arrivals from underground nuclear explosions, Report TR-77-, Teledyne Geotech, Alexandria, Virginia.

Spence, W., 1974. P-wave residual differences and inferences on an upper mantle source for the Silent Canyon volcanic center, southern Great Basin, Nevada, Geophys. J., 38, 505-523.

Hudson, J. A., and A. Douglas, 1975. On the amplitudes of seismic waves, Geophys. J., 42, 1039-1044.

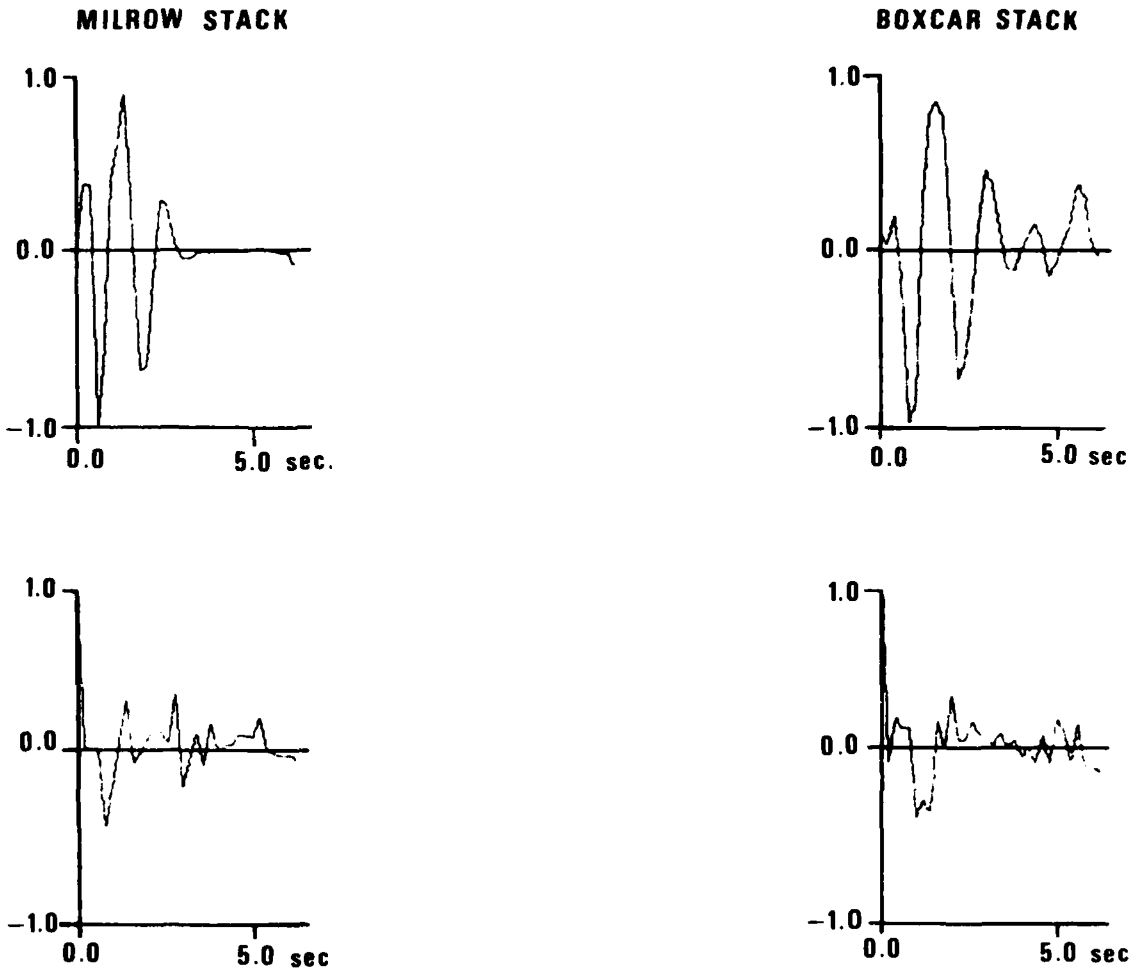

Figure 2 Homomorphic filtering results for MILROW and BOXCAR.

the source time functions. The spall signal for BOXCAR appears about two or three seconds after origin time. Though apparently it is not as large as MILROW'S, equality of spall signals should not be ruled out on the basis of this data. In principle, presence of a small arrival two-tenths of a second after P for BOXCAR might disturb the amplitude of the first half cycle; yet the amplitude as reported above was less than that of MILROW by $0.2m_b$ (Table III), nearly identical to the routine m_b difference. Theoretical synthetic wave form calculation show that the pP delay time difference found in these calculations between MILROW (0.8 sec) and BOXCAR (1.0 sec) will affect the maximum amplitude of the waveforms by less than $0.05m_b$.

Effect of Source Structure

As discussed above, Hudson and Douglas (1975) showed by theoretical short-period seismogram computations that teleseismic amplitude increases roughly proportional to the factor $(\rho\alpha^3)^{-1}$ in the source layer. While values in Table I for the two explosions indicated that a negligible difference exists in this factor at the shot point, note that the overburden value of $(\rho\alpha^3)^{-1}$ for BOXCAR is greater then that of MILROW, as indicated by the reported uphole times. The effect then should increase BOXCAR'S teleseismic pP amplitude, with poor surface reflection this might have only a small effect on m_b. Although the exact nature and effect of the BOXCAR phase 0.2 seconds after origin time, as revealed by the complex cepstrum analysis, cannot be described, it may be due to the laterally varying structure under Pahute Mesa (Spence, 1974).

The effect of a deeper source structure on amplitudes from MILROW is identical to those already described by Jacob (1972) or Davies and Julian (1972) for LONG SHOT. The primary feature in the amplitude pattern is a broad shadow zone created by the downgoing slab's influence on raypaths. This zone, inferred by

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Jacob, K. H., 1972. Global tectonic implications of anomalous seismic P travel times from the nuclear explosion Long Shot, J. Geophys. Res., 77, 2556-2573.

Davies, D., and B. R. Julian, 1972. A study of short-period P-wave signals from Long Shot, Geophys. J., 29, 185-202.

Davies and Julian, is outlined in Figure 1b so that an assessment can be made of the bias of the WWSSN m_b due to the zone. Examination of Figure 1b reveals that the bias should be negligible; if it were significant and corrections made for it, then the need would exist to explain an even larger MILROW magnitude relative to BOXCAR.

Attenuation

Recently, Der and McElfresh (1976) estimated the attenuation coefficient in the Western United States by the use of explosion data in the relation: $S(f) = A(f)\, e^{-\pi f t^*}$ where A(f) is the assumed source spectrum, S(f) is the observed spectrum corrected for instrument response, and t* is the attenuation coefficient. Their data indicates t* of .4 - .5 for paths from NTS explosions to eastern or northern American sites. Frasier and Filson (1972), also observed this value for the path from NTS to the NORSAR array. Of stations yielding digitized P-waves, the most suitable for a comparative t* analysis between BOXCAR ana MILROW would be EKA because it is nearly equidistant from the two explosions and still within the teleseismic range. Figure 3 shows the log spectral ratio of the EKA recordings of the two shots, where equal signal lengths of 6.4 seconds and a spectral band from 0.3 to 3.2 Hz are represented. By computing spectra of noise immediately before the signals, this band was determined to have S/N > 2 in both cases. The slope of this log ratio was computed as -.29 sec satisfying the relation

$$\text{slope} = (\log_{10} e)\ \pi\ (t^*_M - t^*_B)$$

After substituting an assumed $t^*_B = .45$, the resulting attenuation coefficient for MILROW is $t^*_M = .24$. This result is valid only if source spectra are equivalent, a condition which is reasonable considering the similarity in shot media. The result is consistent with existing knowledge of the Q structure under the

Frasier, C. W., and J. Filson, 1972. A direct measurement of the Earth's short-period attenuation along a teleseismic ray path, J. Geophys. Res., 77, 3782-3787.

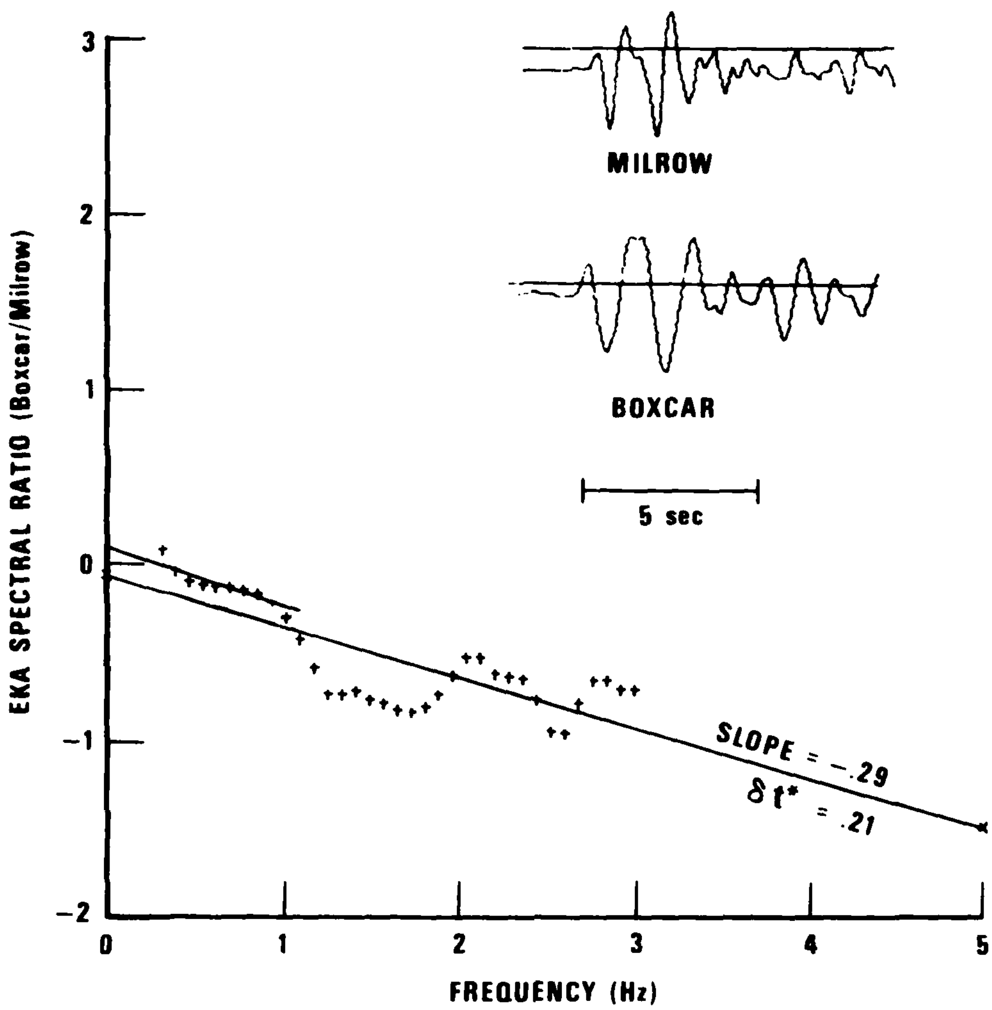

Figure 3 Spectra for MILROW and BOXCAR P-waves recorded at the EKA array. Note extrapolation to 0 Hz.

respective sites. Note that even the first half-cycle of MILROW is of distinctly higher frequency than the same cycle for BOXCAR, showing that the difference in the spectra is not only in the coda. Further, note that extrapolation of the ratio to zero frequency gives an amplitude ratio of 1.25 ± .05 in excellent agreement with the yield ratio 1200/1000. Then the fact that the spectral ratio at 1 Hz is down from that at zero Hz by 0.45 ± 0.1 m_b is consistent with the idea that absorption causes an m_b difference. Note that if the source spectra are of the same shape, absorption is the best remaining explanation for the lower amplitude at 1 Hz compared to zero Hz. Also, it is not necessary to assume any particular $t^*(\omega)$ or $Q(\omega)$ model to reach this conclusion about absorption. The spectral ratio speaks for itself if the source spectra are the same. Although this is only a single station measurement, with the possible exceptions of HNME it is the only suitable common digital station. Furthermore, it has been our experience that spectral measurements are quite stable - as compared to amplitude measurements at any rate.

Returning to the complex cepstra output in Figure 2, note that the deconvolved source pulse for BOXCAR has a broader time dependence than MILROW. We see that this effect is probably a result of failing to remove the differential attenuation.

Theoretical waveform calculations have been performed to show the effect on explosion m_b measured on WWSSN short period instruments for differing t^* of .45 and .24. At one megaton yield for BOXCAR and MILROW pP delays, it amounts to roughly .2 m_b. This figure may be compared to the 0.34 value measured by the WWSSN network analyzed in this study. Thus, Q differences for the structures under the ATS and the NTS sites can explain much of the m_b yield discrepancy between BOXCAR and MILROW.

P-wave coda amplitudes provide an indirect suggestion of higher attenuation for the BOXCAR P-waves. Figure 4 presents 60-second coda measurements on a suite of 18 WWSSN stations common to the two shots. This group of stations is basically the same as in Figures 1a and 1b, less a few stations where the noise background exceeded the P coda within 60 sec. The initial P-wave maximum used

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Douglas, A., P. D. Marshall, P. G. Gibbs, J. B. Young, and C. Blamey, 1973. P-signal complexity re-examined, Geophys. J., 33, 195-233.

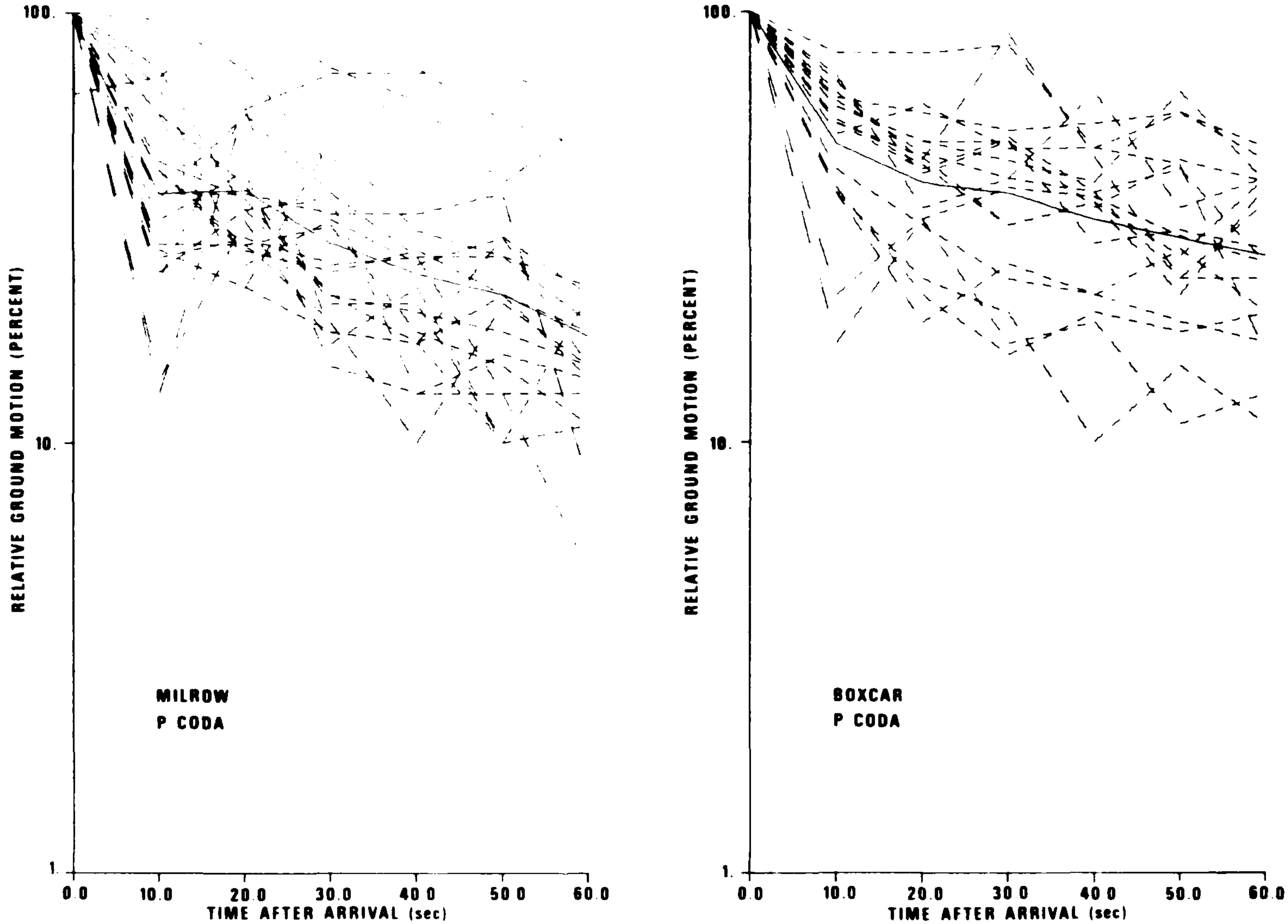

Figure 4 Short-period P-wave coda amplitude at WWSSN stations for BOXCAR and MILROW. Distance range of 30°-87°.

for the m_b measurement is the 100% amplitude level in these figures. Note that BOXCAR codas are typically higher relative to the initial P than the MILROW ones, a phenomenon found by Douglas et al. (1973) to be characteristic of signals from low-Q source regions.

Douglas, A., P. D. Marshall, P. G. Gibbs, J. B. Young, and C. Blamey, 1973. P-signal complexity re-examined, Geophys. J., 33, 195-233.

COMPARISON OF RAYLEIGH-WAVE MAGNITUDE

Previously reported M_s estimates for MILROW and BOXCAR listed in Table II indicate a slightly higher M_s for BOXCAR of perhaps 0.1 to 0.2. Note that all estimates are based upon networks which were limited in the number of stations and which had poor distribution globally relative to the two test sites. In addition, although various "corrections" have been applied to the observations, they do not provide precision M_s estimates for the two shots. Therefore, new M_s estimates for BOXCAR and MILROW were made for this study after examining all WWSSN recordings for BOXCAR and MILROW for detection of Rayleigh-waves. Measurements of the maximum vertical-component amplitude in the 17-23 second period range were used to calculate M_s according to

$$M_s = \log \frac{A}{T} + 1.66 \log \Delta$$

where A is the maximum peak-to-peak amplitude reduced to nm of ground displacement, T is the period of the maximum amplitude, and Δ is epicentral distance in degrees. An earthquake in the Phillipines, reported in the NEIS bulletin, created interference for some of the MILROW signals; measurements were avoided in cases where this interference was thought detrimental. The fact that many more WWSSN stations detected BOXCAR LR immediately revealed a gross difference in the MILROW and BOXCAR M_s. Since clear MILROW LR was obtained only at fourteen stations where LR was also detected for BOXCAR, a method of extending the MILROW coverage was needed for obtaining a large common network of stations teleseismic from both shots for BOXCAR-MILROW Ms comparison. This method involved measuring LR for CANNIKIN, the third nuclear test at ATS with a reported yield of less than five megatons, and extrapolating MILROW M_s from CANNIKIN. Their LR amplitude ratios are listed in Table IV; these ratios are based on identical cycles in the two wavetrains. The log ratios were averaged to obtain a .77 M_s difference between the two ATS shots. This implies an amplitude ratio of 5.9, that also must be the yield ratio under a cube-root scaling assumption and in this context is a number inconsistent with the reported yields of 1000 and 5000 kilotons. This 5.9 ratio is established to within approximately ± 0.6 at the 95% confidence level on the basis of the thirty ratio measurements. Using the -.77 M_s difference, we extrapolated CANNIKIN measurements of LR to a MILROW-equivalent reading at those remaining WWSSN stations with recorded BOXCAR

TABLE IV

LR Ratios for CANNIKIN/MILROW at WWSSN Stations

Station	E-S Az	Ratio $\frac{C}{M}$	Log Ratio
AAM	56	6.7	.83
ALQ	76	6.7	.83
BKS	84	6.7	.83
BLA	57	7.1	.85
CHG	274	8.3	.92
COR	77	6.7	.83
CTA	211	3.5	.54
DUG	75	8.3	.92
GUA	228	5.9	.77
HNR	201	5.0	.70
IST	337	5.0	.70
JCT	76	5.6	.75
KBL	306	11.1	1.05
KON	354	3.0	.48
LON	73	5.3	.72
MAL	2	3.5	.54
MAT	258	6.3	.80
NDI	297	8.3	.92
NOR	3	4.6	.66
NUR	346	3.0	.48
OGD	51	6.7	.83
OXF	65	7.7	.89
PMG	214	3.9	.59
QUE	305	12.5	1.10
SCP	53	4.8	.68
SDB	337	5.3	.72
SHL	284	5.9	.77
TRI	349	4.2	.62
TRN	60	10.0	1.00
WES	48	6.7	.83
Mean			.77
Standard deviation			.16

ratio of yields is antilog (.772) = 5.92

but not MILROW. The M_s results for a thirty-eight station network "common" to MILROW and BOXCAR are listed in Table V; those stations with actual not extrapolated, MILROW measurements are noted the distribution of this common network relative to the two shots is shown in Figures 5a and 5b. The network M_s difference is .59, with 95% confidence intervals of ± .06 on both BOXCAR and MILROW M_s. If the network M_s from the fourteen actual MILROW recordings is compared with the corresponding BOXCAR fourteen-station network M_s, the difference is very near 0.59 with only slightly larger confidence intervals on the two network means; this result supports the validity of our CANNIKIN-MILROW extrapolation procedure, but does not guarantee it. Any systematic departures of individual CANNIKIN/MILROW LR ratios from the mean indicate source effects that might bias the extrapolation. Figure 6 shows such departures in a plot of the thirty observed ratios versus azimuth, and the azimuthal coverage seems sufficient to suppress any significant bias. A composite LR radiation pattern (explosion and tectonic strain release) that Toksöz and Kehrer (1972b) determined for CANNIKIN is superimposed on this figure. If this pattern is appropriate for CANNIKIN, then it probably also serves in a like sense for MILROW. However, the much smaller M_s of MILROW relative to BOXCAR indicates that this phenomenon does not at least significantly increase the MILROW M_s.

Toksöz, M. N., and H. H. Kehrer, 1972b. Tectonic strain release characteristics of CANNIKIN, <u>Bull. Seism. Soc. Am.</u>, <u>62</u>, 1425-1438.

TABLE V

WWSSN M_s estimates for MILROW and BOXCAR

Station	BOXCAR M_s	MILROW M_s
ADE	5.56	5.25
AKU	5.74	5.04
ANP	5.51	4.95
ATU	5.62	5.18
BHP	5.37	4.65
BUL	5.77	4.92
CHG	5.37	4.57*
COP	5.25	4.81
CTA	5.79	5.05*
DAV	5.75	4.95
ESK	5.77	4.84
GRM	5.60	5.28
GUA	5.23	4.77*
HKC	5.31	4.65
HNR	5.67	5.11
IST	5.59	5.19*
KIP	5.33	4.69
KTG	5.58	4.99
LPB	5.28	4.78
MAT	5.51	5.03*
MSH	5.76	5.05
MUN	5.63	4.91
NDI	5.81	4.93*
NOR	6.02	5.06*
NUR	5.63	5.33*
OXF	5.01	4.74
PMG	5.78	5.20*
PRE	5.91	5.07
PTO	5.47	4.93
QUE	5.70	5.04*
RIV	5.44	4.87

TABLE V (continued)

WWSSN M_s estimates for MILROW and BOXCAR

Station	Boxcar M_s	Milrow M_s
SDB	5.57	5.26*
SHI	5.60	5.21
SHL	5.48	4.86*
TRI	5.72	5.11*
TRN	5.50	5.57*
VAL	5.70	4.92
WIN	5.76	5.05
Mean	5.58	4.99
Standard deviation	.21	.21

* Original MILROW Measurements, all others extrapolated from CANNIKIN.

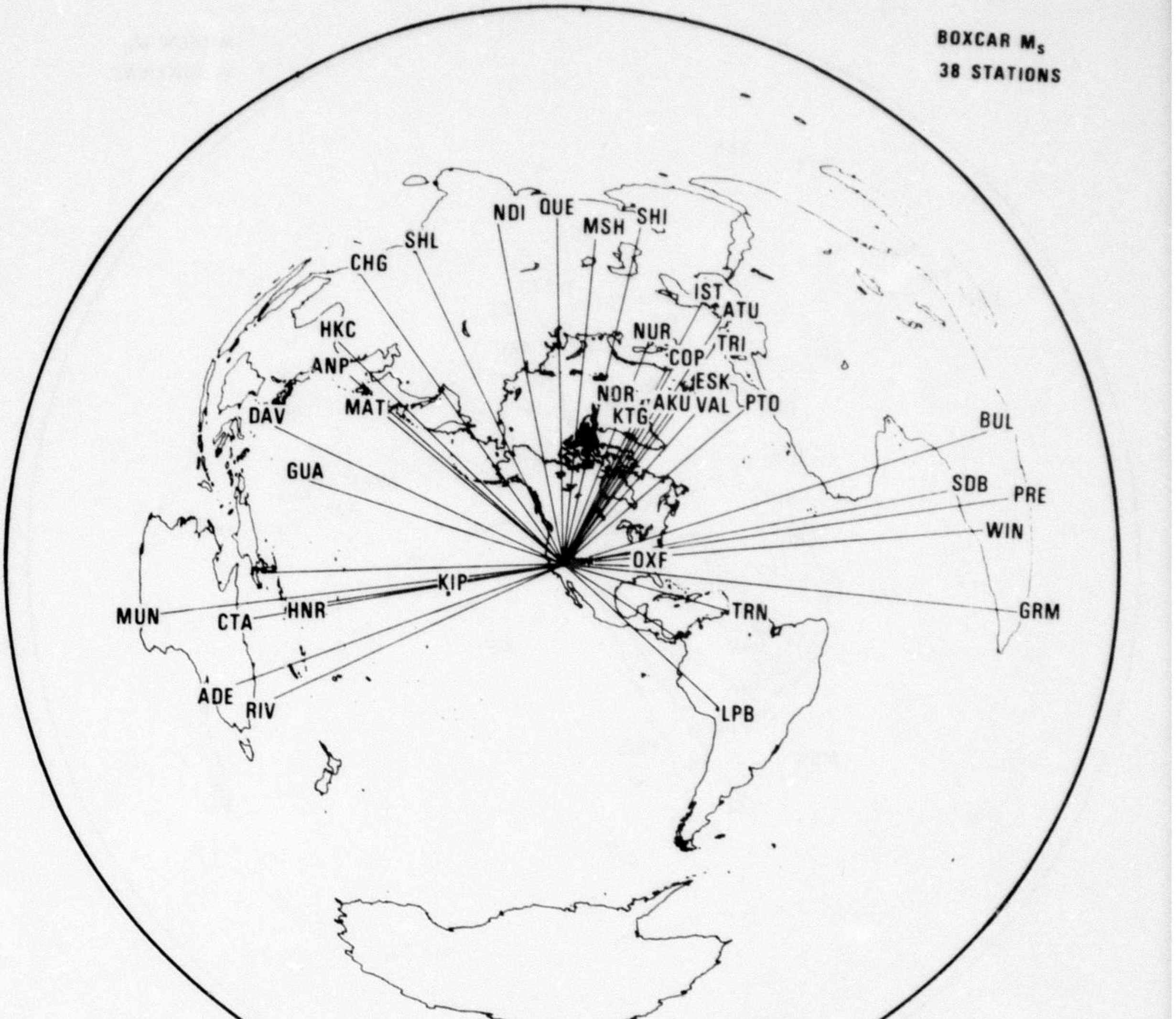

Figure 5a Locations of WWSSN stations used to estimate BOXCAR M_s (equidistant azimuthal projection from the Nevada Test Site).

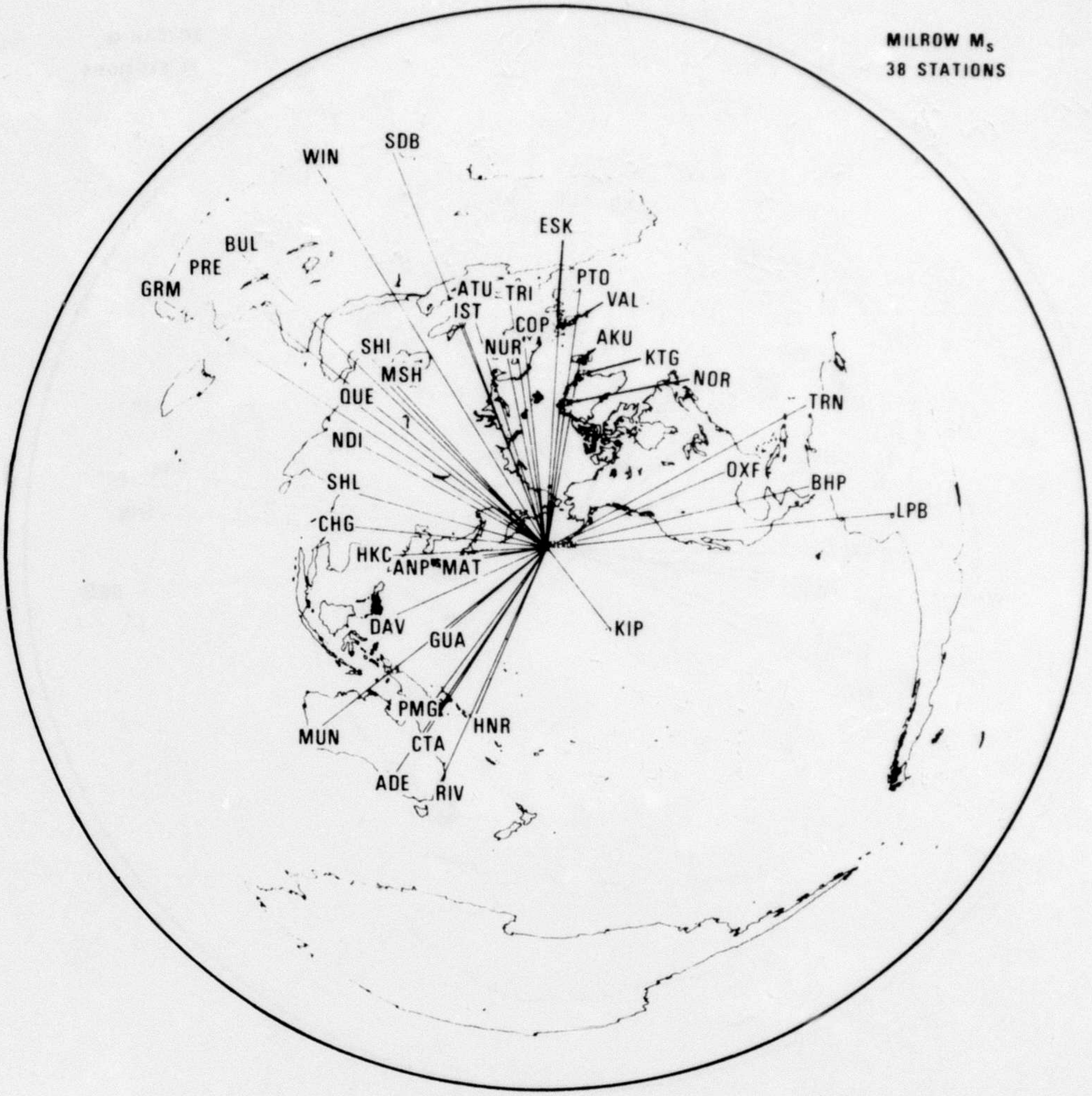

Figure 5b Locations of WWSSN stations used to estimate MILROW M_s (equidistant azimuthal projection from Amchitka Island).

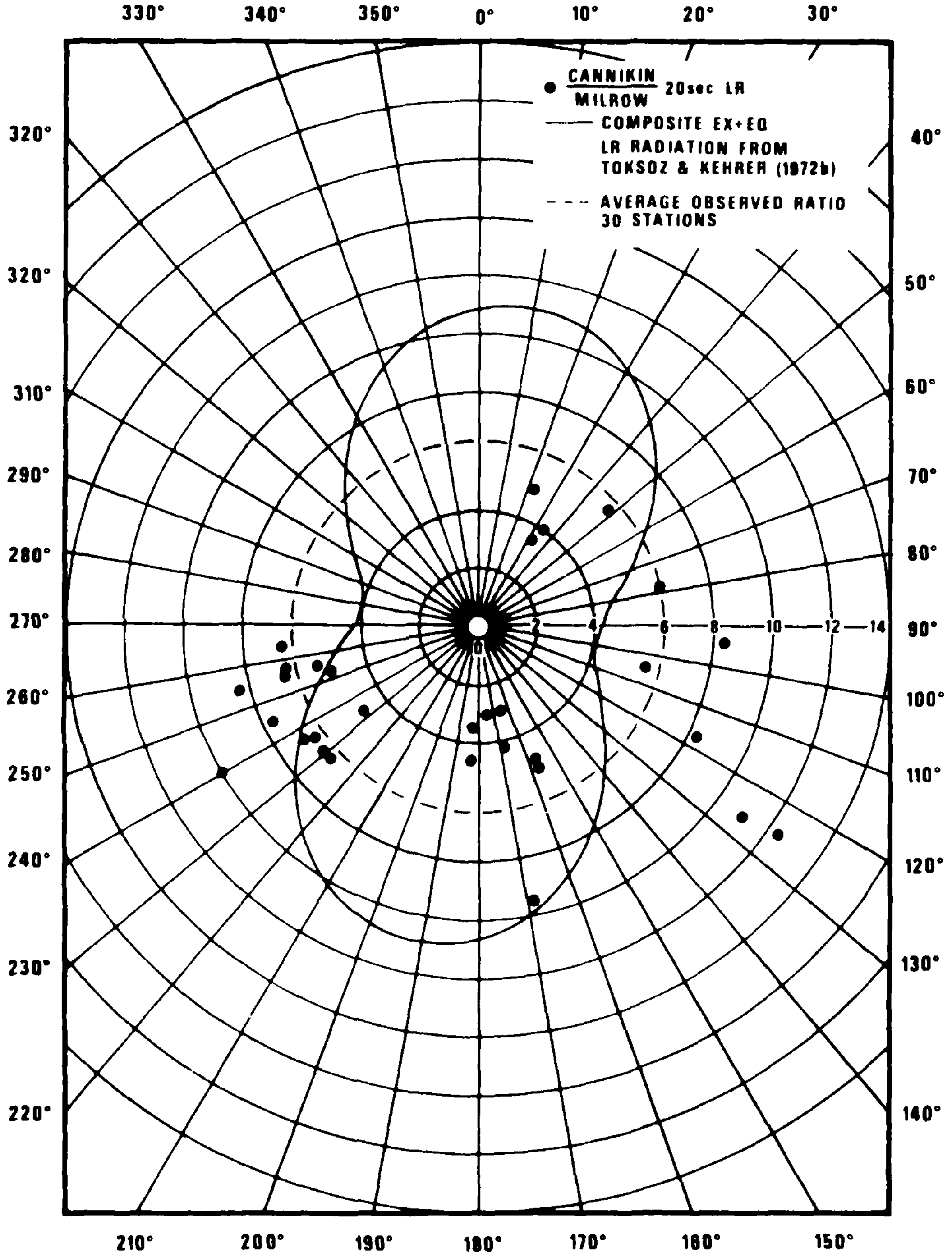

Figure 6 Azimuthal plot of LR ratios for CANNIKIN/MILROW measured at WWSSN stations.

CAUSES OF M_s BIAS

Based upon measurements from a large well-distributed network, the M_s of MILROW was set at 0.59 less than for BOXCAR. This figure could be reduced to 0.52 if correction for the yield difference (1200/1000) were made. This observation may be caused by differences in one or more factors including source coupling, spall effects, structure-dependent LR excitation, tectonic strain release, scattering, refraction of LR wavefronts, and attenuation.

Coupling

Excitation of Rayleigh waves is dependent on either the static, or residual value of the time function for the reduced displacement potential at the elastic radius or the static pressure at this radius. von Seggern and Rivers (1977) gave the full expression for the spectrum of the vertical-component Rayleigh wave recorded from an explosive source buried near the surface as

$$U_z(\omega) = \left(\frac{2}{\pi}\right)^{1/2} \frac{\beta^2}{\alpha^2} M_o S(\omega) \left(\frac{\omega}{C_R(\omega)}\right)^{-1/2} A_R(\omega) \frac{U_h}{W_o}(\omega)\, R_o^{-1/2}$$

$$\sin^{-1/2}\left(\frac{r}{R_o}\right) \exp[-\omega r/2Q(\omega)U_R(\omega)] \quad \exp\{i[\omega(t-\frac{r}{C(\omega)}) + \frac{3\pi}{4}]\}. \quad (1)$$

Rather than listing the variables here, they will be described only as needed in this and subsequent sections.

Tsai and Aki (1971) showed

$$M_o = 4\pi\rho\alpha^2 \, [\Psi\,(t)]_{\,t \to \infty}$$

and as Love (1944) showed

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von Seggern, D. H., and D. W. Rivers, 1977. Seismic discrimination between earthquakes and underground explosions in the southwestern United States Report SDAC-TR-77-10, Teledyne Geotech, Alexandria, Virginia.

Tsai, Y. B., and K. Aki, 1971. Amplitude spectra of surface waves from small earthquakes and underground nuclear explosions, J. Geophys. Res., 76, 3940-3952.

Love, A. E. H., 1974. A Treatise on the Mathematical Theory of Elasticity, Dover Publications, New York, New York.

$$M_o = \frac{\pi\alpha^2 R_e^3}{\beta^2} \quad P(t)_{t \to \infty}$$

so that either the residual pressure P (∞) or the residual RDP $\Psi(\infty)$ can be used to scale Rayleigh waves. These quantities, plus the ratio β^2/α^2, are related to the immediate source environment while other factors in this equation are related to the structural model, assumed to be plane-layered, that characterizes the total medium.

Sufficient near-field data are not available for either BOXCAR or MILROW to quantify the values of $\Psi(\infty)$ or $P(\infty)$. A number of authors, through the use of teleseismic data have made estimates of these parameters, but such conclusions would produce a circular argument if used to explain the large observed teleseismic M_s differences. Assume that, similar to previous arguments for nearly equivalent short-period source functions, the differences in $\Psi(\infty)$ and $P(\infty)$ for the two shots is small. Also no significant difference is expected in the quantity β^2/α^2 on the basis of the known lithology surrounding the two-shot points. Thus coupling does not seem to explain the large M_s difference of BOXCAR and MILROW.

Secondary Phases

The expression β^2/α^2 for the observed Rayleigh-wave spectrum assumes a perfectly elastic response to a point source and perfect reflection across the entire spectrum at the free surface (Harkrider, 1964). The spalling phenomenon violates these assumptions and transfers a portion of the pP energy into spall energy. If the explosion source function is a step function of pressure and the spall is an impulsive force, then Harkrider's (1964) relations result in equivalently shaped Rayleigh-wave spectra. Gupta and Kisslinger's (1964) expressions for Rayleigh-waves in a half-space demonstrated this equivalence. A phase advance of $\frac{\pi}{4}$ radians exists for the spall signal relative to that of the explosion, however. Viecelli's (1973) numerical integration work

Harkrider, D. G., 1964: Surface waves in multilayered elastic media. 1. Rayleigh and Love waves from buried sources in a multilayered elastic half-space, Bull. Seism. Soc. Am., 54, 627-680.

Gupta, I. N., and C. Kisslinger, 1964: Model study of explosion-generated Rayleigh waves in a half space, Bull. Seism. Soc. Am., 54, 475-484.

resulted in signal amplitudes larger by a factor of two or more for a spall + explosion model than for an explosion one alone. However, these results are not directly applicable to the M_s measurements because they are displayed as velocity time series and they had a dominant period roughly an order of magnitude less than twenty seconds due to the limited scale of the finite-difference model. Because MILROW and BOXCAR had only partial conversion of pP energy to spall energy, revealed by the complex cepstra results, only a small part of the difference in teleseismic M_s can be attributed to different effects of pP and spall for the two shots.

Tectonic Strain Release

Toksöz and Kehrer (1972a), in a thorough study of the experience with tectonic strain release at the NTS, estimated the ΔM_s that could be caused by addition of tectonic Rayleigh-wave excitation which was activated by explosive sources. They estimated the relative component of tectonic strain release (their F factor) for BOXCAR to be $\sim .6$. According to their tables, this translates to an increase of about 0.1 M_s unit for 20-second M_s as measured by a network well-distributed in azimuth. Since the WWSSN network is sufficiently distributed (Figure 5a) to suppress any systematic bias due to recording on the lobes or nodes of composite radiation pattern, the BOXCAR M_s should accurately reflect the predicted increase because of the tectonic strain release component. Figure 7, however, shows that observed magnitudes do not correlate well with the predicted composite radiation pattern, and a question emerges of whether the BOXCAR tectonic component is as large as Toksöz and Kehrer determined.

Viecelli, J. A., 1973: Spallation and the generation of surface waves by an underground explosion, J. Geophys. Res., 78, 2475-2487.

Toksöz, M. N., and H. H. Kehrer, 1971: Underground nuclear explosions: tectonic utility and dangers, Science, 173, 230-233.

Toksöz, M. N., and H. H. Kehrer, 1972a: Tectonic strain release by underground nuclear explosions and its effect on seismic discrimination, Geophys. J., 31, 141-161.

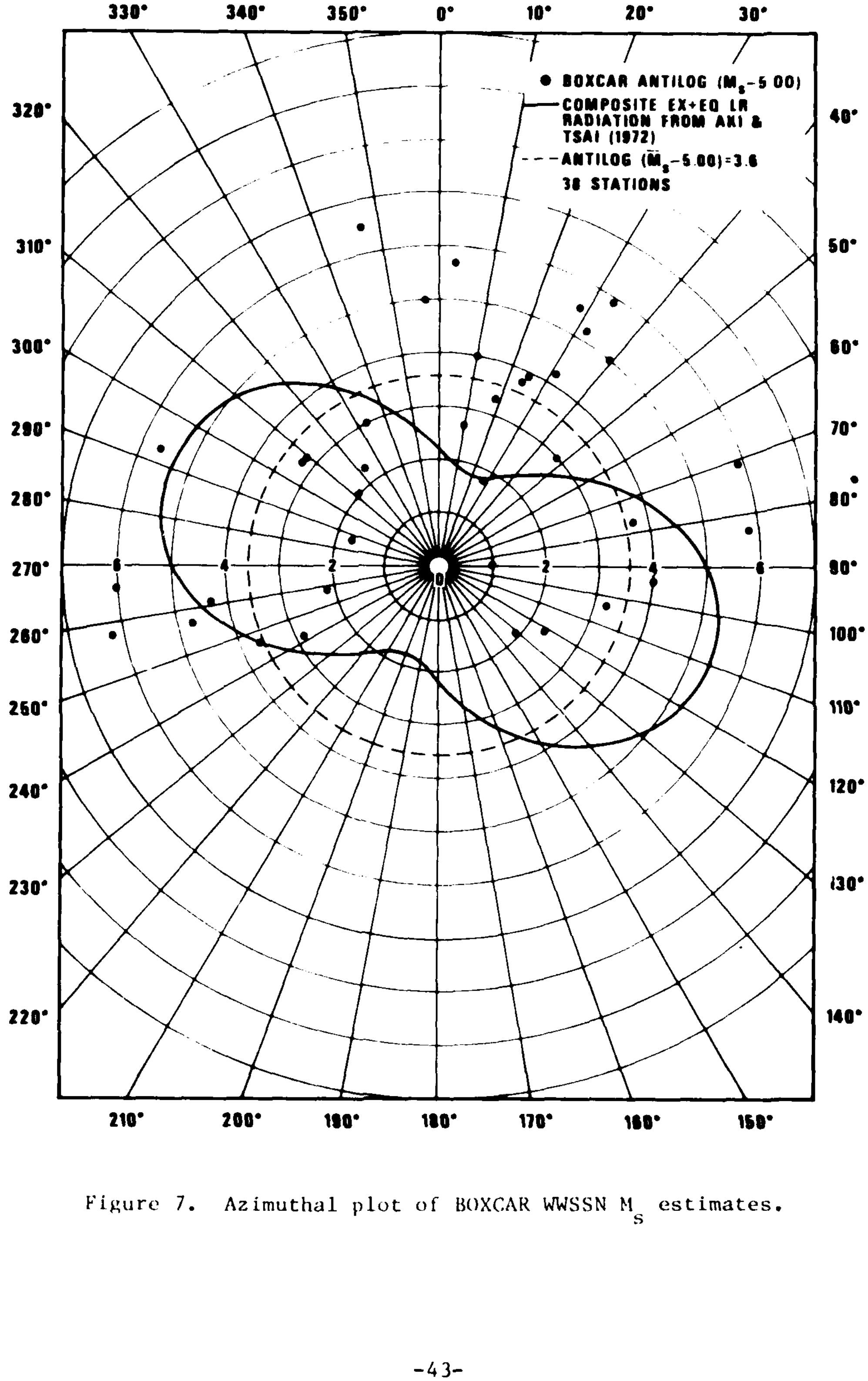

Figure 7. Azimuthal plot of BOXCAR WWSSN M_s estimates.

Hypothesizing MILROW tectonic strain release, Toksöz and Kehrer (1971) determined an F ratio of tectonic strain release to explosion of < 0.6 on the basis of a few recordings. This 0.6 figure would seem to be liberal upper limit in light of the negative view towards significant tectonic strain release at the ATS expressed by Engdahl (1972) on the basis of seismicity studies and by von Seggern (1973) on the basis of observed Rayleigh and Love waves. Toksöz and Kehrer (1972b) were able to analyze a larger number of recordings for the CANNIKIN event and determined F = 0.6 for that explosion. Figure 8 shows the WWSSN M_s estimates for CANNIKIN with the composite radiation pattern of Toksöz and Kehrer superimposed on it. Little exists in these observations supporting the significant tectonic component that Toksöz and Kehrer determined from Love/Rayleigh ratios. Visual examination of their plotted observations demonstrates that they do not fit their inferred composite radiation pattern well and that there is a large proportion of noise in their inversion of the data. An alternate explanation for the appearance of the MILROW and CANNIKIN Love waves is mode conversion. Von Seggern (1973) suggested this process when he found Love waves from the MILROW collapse by match filtering. The collapse, a process which should be devoid of Love-wave generation, leaves mode conversion as the explanation.

Structure Effects

For a given seismic moment, the spectral distribution of Rayleigh-wave excitation is dependent upon the structure. Von Seggern (1971) compiled the excitation level of twenty second LR for numerous different structural models and showed that this value could vary as much as a factor of about two. Hudson and Douglas (1975) also showed how M_s is affected by the actual earth model used in the calculation of synthetic signals, according to a relation similar to (1). A linear relation of the form $A_R = -7.6C_R + 33.0$ fits the

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Engdahl, E. R., 1972: Seismic effects of the MILROW and CANNIKIN nuclear explosions, Bull. Seism. Soc. Am., 62, 1411-1423.

von Seggern, D. H., 1973: Seismic surface waves from Amchitka Island test site events and their relations to source mechanism, J. Geophys. Res., 78, 2467-2474.

von Seggern, D. H., 1971: Effects of propagation paths on surface-wave magnitude estimates, Report SDL-279, Teledyne Geotech, Alexandria, VA.

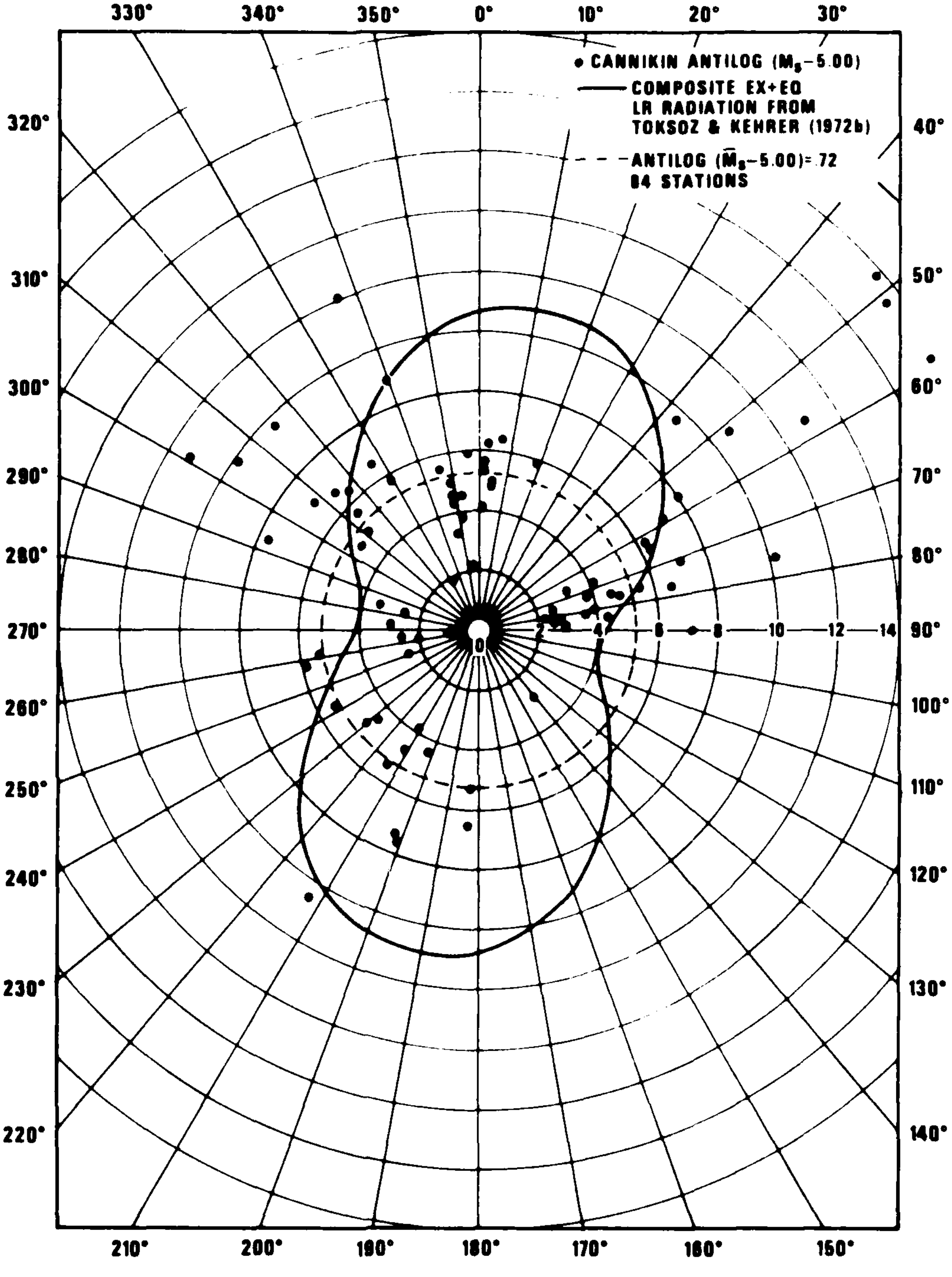

Figure 8 Azimuthal plot of CANNIKIN WWSSN M_s estimates.

data points of von Seggern (1971) for twenty-second LR waves such that the scatter does not exceed 10%. A_R is the excitation factor in (1) with units of 10^{11} nm/dyne, and C_R is the phase velocity. The phase velocity for the structure beneath Amchitka Island at a period of 20 sec is roughly 3.6 km/sec (Jacobs and Kamada, 1972) while the phase velocity for NTS is certainly no higher and may be as low as 3.3 km/sec (Ewing and Press, 1969) because of a relatively shallow crust and some influence of low upper-mantle velocities on the phase velocity of 20-sec LR. Under any reasonable assumptions then, the empirical relation for A_R does not explain any of the observed M_s difference between BOXCAR and MILROW since it would predict higher MILROW amplitudes. One could regard the Amchitka structure as oceanic. Then, perhaps 0.35 M_s of the difference could be explained.

The effect of the dipping lithospheric plate beneath the ATS on 20-sec Rayleigh waves is probably not significant since this anomalous structure exists in the upper mantle and not in the crust where 20-sec LR is largely confined. Goforth (1976) investigated LR excitation by surface point sources over such a structure with a simple laboratory model and found no significant difference for 20-sec LR excitation between this structure and a plane-parallel layered model.

Path Effects

The great-circle paths from the two shots to the thirty-eight common stations of the WWSSN were shown in Figures 5a and 5b. Aspects of the travel paths that might be considered contributors to the M_s difference are the amount of oceanic vs. continental path, the number and angle of major geophysical boundary crossings, and the presence of inhomogeneities that might cause focusing or defocusing.

Figures 5a and 5b show that the proportion of oceanic structure in the total travel path for the BOXCAR shot is roughly double that for MILROW but, it is still only one-half the total. Differences in recorded amplitude can arise from equation (1) if differences in the term

$$\gamma_R(\omega) = \omega/2Q(\omega)U_R(\omega)$$

Goforth, T. T., 1976: A model study of the effect on the Rayleigh spectrum of lateral heterogeneity in earthquake source regions, J. Geophys. Res., 81, 3599-3606.

Ewing, M., and F. Press, 1959, Determination of crustal structure from phase velocity of Rayleigh waves, Part III: The United States; Bull. Geol. Soc. Am., 70, 229-244.

exist for oceanic and continental structure. Mitchell et al. (1976) estimated $\gamma_R \approx .00025\ km^{-1}$ for the Pacific Ocean at a period of 20 seconds. For continents, Mitchell (1973) measured $\gamma_R \approx .0001\ km^{-1}$ for eastern and central U.S. at this period while Burton (1974) measured $.00015 < \gamma_R < .00030$ for continental paths from the U.S.S.R. and China explosions. These empirical results, coupled with actual MILROW-BOXCAR paths suggest that, on the average, the greater amount of attenuation is suffered by the BOXCAR LR waves, an implication that runs contrary to higher BOXCAR M_s measured by the WWSSN stations. Therefore, differing attenuation is most likely not a cause of the MILROW-BOXCAR M_s difference.

The effect of the earth's lateral inhomogeneities on MILROW and BOXCAR LR amplitudes is probably negligible when only far-field propogation is considered. Regarding crossing major structural boundaries, BOXCAR Rayleigh waves meet more ocean-continent boundaries, but still average higher in amplitude. Thus, losses in transmission at these points is not causing the pronounced M_s difference. Focusing and defocusing of 20-sec Rayleigh waves, due to laterally inhomogeneous crustal structure over the globe (von Seggern et al., 1975) would because of the well-distributed sample points in our M_s estimation tend to average out to insignificant overall effects on the M_s values for each shot. However, these arguments for negligible path effects would not apply

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Mitchell, B.J., L.W.B. Leite, Y.K. Yu, and R.B. Herrmann, 1976, Attenuation of Love and Rayleigh waves across the Pacific at periods between 15 and 110 seconds, Bull. Seism. Soc. Am., 66, 1181-1202.

Mitchell, B. J., 1973: Surface-wave attenuation and crustal inelasticity in central North America, Bull. Seism. Soc. Am., 63, 1057-1071.

Burton, P. M., 1974. Estimations of Q_γ^{-1} from seismic Rayleigh waves, Geophys, J., 36, 1670-190.

von Seggern, D. H., P. A. Sobel, and D. W. Rivers, 1975: Experiments in refining M_s estimates for seismic events, Report SDAC-TR-75-17, Teledyne Geotech, Alexandria, VA

von Seggern, D. H., 1973: Seismic surface waves from Amchitka Island test site events and their relation to source mechanism, J. Geophys. Res., 78, 2467-2474.

if the major structural boundaries occur in the near field, within a few wavelengths of the source, which is true for the Aleutian structure around MILROW. Study of the effects of major close-in structural changes requires three-dimensional numerical calculations not yet feasible. Simply on the basis of having rejected every other possible cause of the low MILROW M_s, (except possible oceanic structure at MILROW), we hypothesize that some significant loss in LR 20-sec energy occurs near the source. This hypothesis is indirectly supported by the fact that for the MILROW collapse (von Seggern, 1973) Love waves are recorded at a time consistent with conversion from Rayleigh waves near to the source. Following von Seggern (1973), an assumption that at least half of the observed amplitude of MILROW and CANNIKIN Love waves are a result of conversion helps to explain the poor fit that Toksöz and Kehrer (1972b) obtained with a composite radiation pattern to observed LQ/LR ratios for CANNIKIN. The Rayleigh-to-Love conversion suggested here cannot account for the full 0.6 M_s difference between MILROW and BOXCAR, only perhaps 0.2.

In Figure 9 are the Rayleigh-wave spectra from the LP vertical recordings made at NP-NT of MILROW and BOXCAR. This LRSM station is nearly equidistant from both explosions, the great-circle path is over continental structure in both cases, and its recordings reflect the typical differences between the 20-sec LR of the two shots. The spectra are scaled absolutely and have good S/N ratios over the bandwidth shown. At f = .05 hz the BOXCAR spectrum is a factor at least two higher than that of MILROW. The difference becomes small at lower frequencies and suggests near equivalence at f = .025 hz or 40-sec period. Since this period has been suggested as a better point for estimating M_s for discrimination (Molnar et al., 1969) and since LR attenuation is thought less variant over the globe at this period, a survey of 40-sec amplitude was made as follows:

Molnar, P., J. Savino, L. R. Sykes, R. C. Liebermann, and G. Hade, 1969: Small earthquakes and explosions in western North America recorded by new high-gain, long-period seismographs, Nature, 224, 1268-1273.

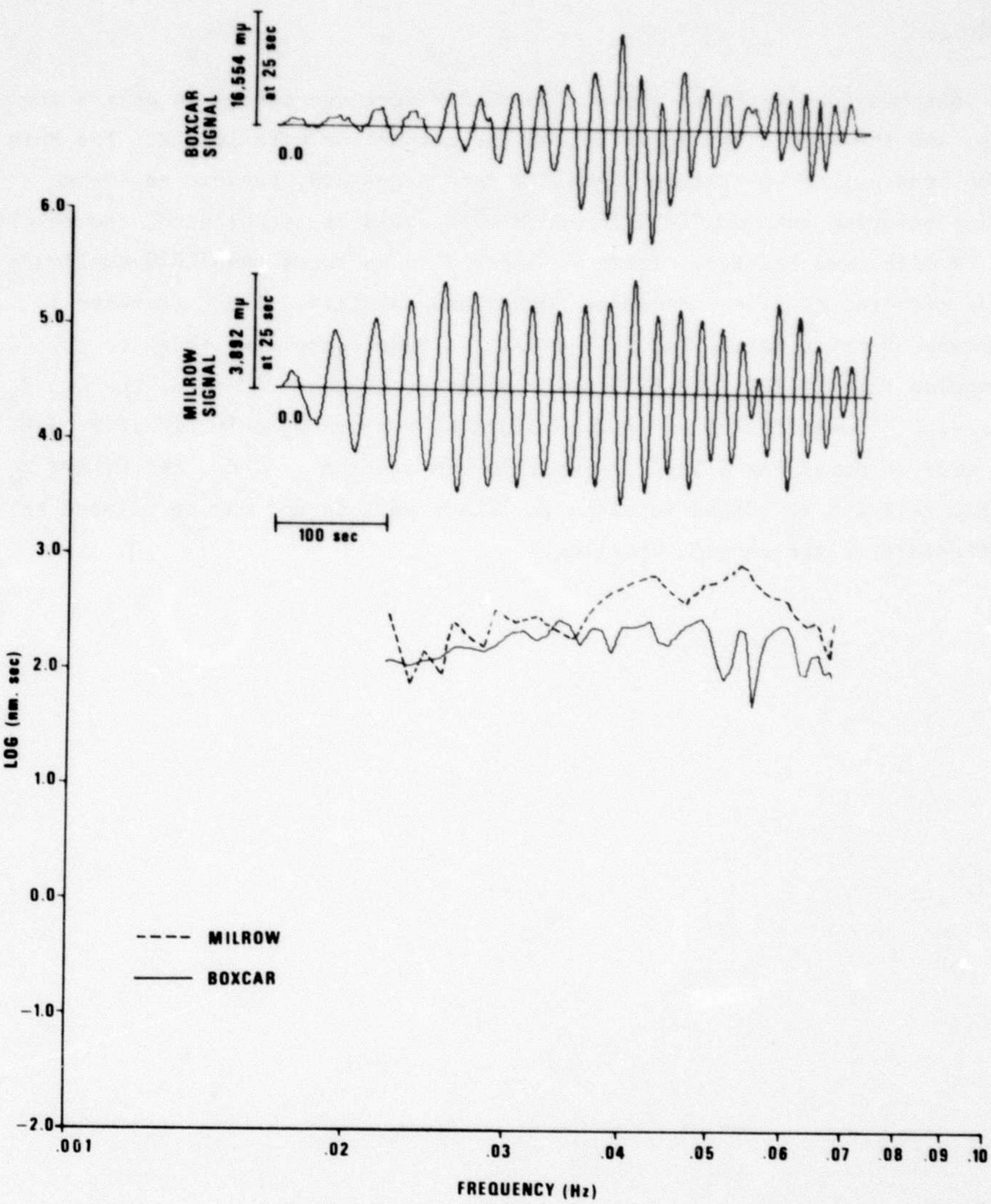

Figure 9 Spectra of vertical-component Rayleigh-waves recorded at NP-NT from MILROW and BOXCAR (instrument response removed).

M_s (40 sec)

Searches for 40-sec LR waves from MILROW were successful in only a few cases, and the sample was insufficient for comparison with BOXCAR. For this reason, the author substituted CANNIKIN recordings and, because no 40-sec scaling relation between CANNIKIN and MILROW could be established, the results will be discussed briefly. Table VI lists data on those LR40/LR20 amplitude ratios measured at sites common to BOXCAR and CANNIKIN. The difference in the means of these ratios is .10 log unit, a result implying that, on the assumption that MILROW LR40/LR20 was similar to that of CANNIKIN, the 0.6 M_s difference between MILROW and BOXCAR could be reduced by only .10 if M_s (40 sec) were computed for a large group of WWSSN stations. Thus, the MILROW M_s anomaly relative to BOXCAR persists to longer periods and may be related to a difference in the source functions.

TABLE VI

40-sec/20-sec amplitude ratios for BOXCAR and CANNIKIN

Station	BOXCAR $\log_{10}\left(\frac{LR40}{LR20}\right)$	CANNIKIN $\log_{10}\left(\frac{LR40}{LR20}\right)$
ATU	- .64	-.96
CHG	- .15	-.21
CTA	- .72	-.20
DAV	- .32	-.23
ESK	- .96	-.30
HNR	- .36	-.28
IST	- .74	-.70
KTG	- .77	-.48
MAT	- .42	-.74
MSH	- .66	-.80
NDI	-1.10	-.72
NUR	- .54	-.43
OXF	- .46	-.22
PMG	- .46	-.19
PRE	- .62	-.26
QUE	- .82	-.72
QUI	- .29	-.17
SHL	- .51	-.38
SJG	- .47	-.64
TRI	- .96	-.82
TRN	- .34	-.74
WIN	- .42	-.40
Mean	- .58	-.48
Standard deviation	.24	.25

HANDLEY AN ALTERNATIVE NTS SHOT

Requirements for clear worldwide WWSSN recording limited the comparison of the Amchitka and Nevada Test Sites to MILROW and one of the NTS megaton-range shots respectively. BOXCAR was chosen for NTS, to match the MILROW shot point parameters. It is of interest to examine a NTS shot where shot point parameter do not match those of MILROW. HANDLEY, 26 March 1970, listed with a yield "> 1 Mt" by Springer and Kinnaman (1971), was selected.

Body-wave magnitudes, computed in the routine manner, from 24 WWSSN stations common to BOXCAR and HANDLEY are listed in Table VII. These comprised all the teleseismic stations for which the comparison could be made. The .19 difference in the mean magnitudes agrees well with the ISC-reported magnitude difference (6.2 for BOXCAR versus 6.4 for HANDLEY).

As discussed in an earlier section, HANDLEY'S shot point parameter can explain this difference via the linear source theory of Hudson and Douglas (1975), but not via the non-linear theory of Cherry et. al. (1975). In any event, the major point is that one is not surprised by a different result, given that the shot point parameters are clearly different.

The surface-wave magnitudes from 49 WWSSN stations common to BOXCAR and HANDLEY are listed in Table VIII. Again, these are the complete WWSSN teleseismic set recording measurable waveforms for both shots. The difference in mean magnitudes, .11, is significant at the 99.9% confidence level, based upon the assumption of normal distributions for the magnitudes. The small difference is again consistent with the linear theory of Hudson and Douglas, and not with the non-linear theory of Cherry et. al.

It must be pointed out that for the linear theory to hold the "non-linear" part of the signal generation must be unaffected by α and ρ. Obviously dry alluvium has smaller α and ρ and smaller signal. If we are to believe the linear theory we must suppose that between BOXCAR and HANDLEY the "non-linear" properties are much the same, even though α and ρ differ. This of course is contradicted by the difference in yield strength (a non-linear property) in Table I, so we are left with a confused situation. Perhaps we must conclude that the yield strength is irrelevant. At least we can say that different source properties correspond to different radiated energy.

TABLE VII

WWSSN m_b estimates for BOXCAR and HANDLEY

Station	BOXCAR m_b	HANDLEY m_b
AFI	6.51	6.56
AKU	5.88	6.08
ANT	6.23	6.39
ARE	6.57	6.78
BEC	6.30	6.35
BHP	5.81	6.04
BOG	6.23	6.68
COP	5.84	6.04
ESK	6.23	6.04
GDH	6.15	6.17
GUA	6.47	6.70
HNR	6.87	7.12
KIP	6.33	6.44
KON	6.11	6.38
KTG	6.18	6.33
MAL	6.19	6.33
NOR	5.57	6.13
NUR	5.87	6.17
PTO	6.02	6.26
QUI	6.53	6.37
TRI	5.63	6.03
TRN	6.19	6.44
VAL	6.06	6.18
WES	6.11	6.46
Mean	6.16	6.35
Standard deviation	.31	.27

TABLE VIII

WWSSN M_s estimates for BOXCAR and HANDLEY

Station	HANDLEY M_s	BOXCAR M_s
AFI	5.24	5.15
AKU	5.72	5.74
ANP	5.27	5.51
ANT	5.02	5.23
ARE	5.18	5.23
ATU	5.55	5.62
BAG	5.38	5.53
BEC	5.42	5.72
BHP	5.30	5.37
CHG	5.47	5.37
COL	5.43	5.48
COP	5.58	5.25
CTA	5.76	5.79
DAV	5.59	5.75
ESK	5.60	5.77
GRM	5.40	5.60
HKC	5.45	5.31
HNR	5.40	5.67
IST	5.53	5.59
KIP	5.16	5.33
KTG	5.68	5.58
LPB	5.37	5.28
MAL	5.35	5.59
MAN	5.32	5.49
MAT	5.39	5.51
MSH	5.69	5.76
MUN	5.36	5.63
NDI	5.89	5.81
NOR	6.02	6.02
NUR	5.66	5.75

TABLE VIII (continued)

WWSSN M_s estimates for BOXCAR and HANDLEY

Station	HANDLEY M_s	BOXCAR M_s
PMG	5.49	5.78
PRE	5.54	5.91
PTO	5.47	5.47
QUE	5.53	5.70
QUI	5.46	5.41
RIV	5.14	5.44
SDB	5.33	5.57
SEO	4.86	5.12
SHI	5.60	5.60
SHL	5.42	5.48
SJG	5.28	5.46
SNG	5.39	5.46
SPA	5.53	5.61
TAB	5.67	5.70
TRI	5.51	5.72
TRN	5.36	5.50
VAL	5.63	5.70
WIN	5.51	5.76
Mean	5.46	5.56
Standard deviation	.21	.20

Although comparison of MILROW M_s with HANDLEY M_s might somewhat narrow the NTS-ATS difference in M_s-yield, the conclusion remains that roughly a half-order of magnitude difference exists.

CONCLUSION

Using a common global recording network of WWSSN stations, an increase of approximately 0.3 m_b unit was determined for the MILROW explosion relative to the BOXCAR explosion, when the small yield difference is accounted for. Although examination of possible causes of this observation indicates that relative attenuation can explain 0.2 of this difference, the explanation for the remainder is not readily apparent. Signal waveform comparison reveals a broader teleseismic pulse for BOXCAR than for MILROW, a fact consistent with higher attenuation under NTS, which is a characteristic of the Basin-Range province. The spectral ratio at one station and coda amplitude measurements support this interpretation also.

Again, with a large and common global WWSSN network, the M_s difference between BOXCAR and MILROW was established as approximately 0.5 M_s unit, when the yield difference is accounted for. In examining possible causes which could contribute to this difference, no single one emerged that explained more than 0.1 or 0.2 of the lower MILROW M_s. With the possible exception of oceanic crust at MILROW. Conversion of Rayleigh waves to Love waves near the MILROW source is probably significant. Still, all the 0.5 M_s difference cannot be satisfactorily accounted for.

The inability to draw definitive conclusions for this study hinges somewhat on the uncertainty in source time functions for both BOXCAR and MILROW. These two explosions were not as well recorded at close-in range as several other U. S. underground nuclear explosions such as SALMON or HARDHAT, and therefore no rigorous independent definition of the reduced displacement potential can be made. Although numerical modeling of nonlinear source dynamics, a possibility with the extent of knowledge of the immediate source environment about BOXCAR and MILROW, was beyond the scope of this report, it would be a worthwhile future study which may resolve the causes of the magnitude differences.

The essential observations of this study are summarized by the M_s-m_b plot for BOXCAR, MILROW and HANDLEY in Figure 10. On this basis NTS and Amchitka appear different in their M_s and m_b character even though surrounding shot media are not appreciably different in their properties. This observation

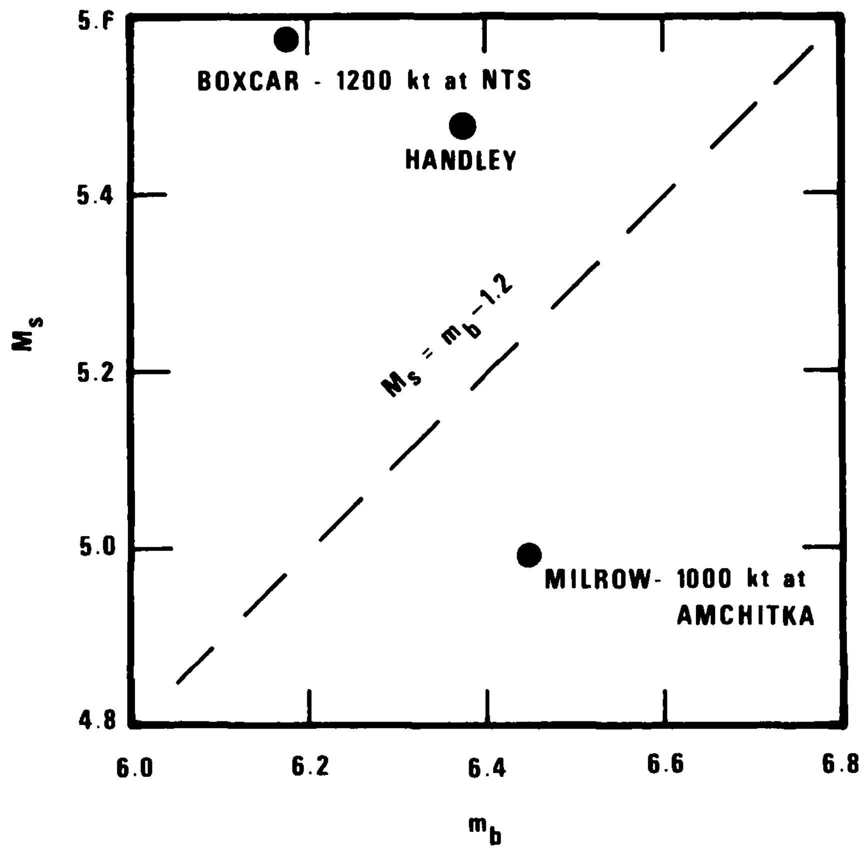

Figure 10. M_s versus m_b for MILROW and BOXCAR.

has serious implications for yield determination by seismic magnitudes. In the case of m_b, our increasing knowledge of the earth's attenuation properties and its relation to other geophysically measurable quantities or structural expressions on the surface possibly will allow accurate corrections to be made _a priori_ for the effect of varying inelasticity. In the case of M_s, the MILROW-BOXCAR discrepancy remains vexatious and casts doubt upon a superior role for M_s in yield determination, which many investigators have recently suggested. However, M_s may still be useful in a general sense because arguments could be made that the Amchitka Test Site is in an extremely anomalous source region whose lateral inhomogeneity is not to be duplicated at other probable nuclear test sites on earth.

This study was performed essentially on only one representative shot from each site. Although the statistician might reasonably require more events to make an intersite magnitude-yield comparison, situations in which only single calibration shots would be available can arise. If these shots were MILROW and BOXCAR, then researchers, on the basis of data presented here, could be forced to infer that the yields were significantly different, one way when using m_b and the other way when using M_s. As this report went on to show, if HANDLEY were the calibration shot, then the problem would at least remain with M_s. This study spotlights the capricious behavior of magnitude as an estimate of yield. Even within Pahute Mesa at NTS, a .2 difference was found in m_b for the two close, well-recorded shots, BOXCAR and HANDLEY. While the shot point media were different for the two events, this difference probably could not have been determined had it existed at a Soviet Test Site.

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